Sulzman FM, Genin AM, eds. *Space Biology and Medicine Volume II: Life Support and habitability.* Washington, DC: American Institute of Aeronautics and Astronautics; 1994.

Chapter 16

Biological Life Support Systems

G. I. Meleshko, Ye. Ya. Shepelev, M. M. Averner, and T. Volk

Since the publication of the first joint work on space biology and medicine in 1975, the status of the problem of the man-rated biological life support systems (BLSS) has altered substantially. What is most important is that the inevitable need for the BLSS for future space programs demanding long-term autonomous human survival far from Earth has become increasingly obvious and has been generally acknowledged. This has led to increased international collaboration and to a substantial expansion of the geography of BLSS research, which is now being conducted in Canada, Japan, and many European countries.

The United States is implementing a program to develop the Controlled Ecological Life Support System (CELSS) for use on Space Station. The CELSS will include a number of BLSS subsystems, especially higher plant subsystems, combined with a physical-chemical regeneration system.

The first ground-based models of the BLSS for humans were developed in the Soviet Union. In the Russian Federation, a new phase in the study of this problem has begun—the study of individual BLSS components and technologies as they function in space with the participation of Mir crews. As a result, this area has now graduated from the status of an intriguing problem to be solved in the distant future to that of an extensive program involving genuine experimental developments.

The use of the principle of the biological substance cycle to support the vital processes of cosmonauts was first proposed by K.E. Tsiolkovskiy as early as 1911.[1] Less than 50 years later, at the start of the space era, the creation of a man-rated BLSS had become a practical goal.

Early discussions of the feasibility of such systems were published in the United States[2–4] and then in the U.S.S.R.[5–8] These discussions gradually generated the conviction that BLSSs were essential to the future of cosmonautics. BLSS concepts that resembled the modern ecological understanding of the term were proposed in the U.S.S.R. in 1963,[8] and were more fully developed in 1966 on the basis of empirical data.[9]

Initial theoretical designs of different variants of bioregenerative systems were based on the data available at the time regarding laboratory and industrial cultivation of one-celled algae, including *Chlorella*. It was believed that these algae could use human waste products as a food source and that their biomass could satisfy human needs for the major nutrients. These ideas led to empirical attempts to create BLSSs for regenerating the atmosphere through *Chlorella* photosynthesis.

American scientists conducted the first experiments using animals (mice) soon after the appearance of the first man-made Earth satellites.[10–12] These experiments were terminated because of the low productivity of algae cultures, which resulted in the accumulation of excess carbon dioxide and failure to produce sufficient oxygen. In 1961, at the USAF School of Aviation Medicine, a 50-h experiment using monkeys was conducted and had a similar result. Experiments conducted by Soviet researchers in 1960 with rats and dogs, lasting 6–8 days, and then with humans (two experiments, each lasting 1-1/2 days) were equally unsuccessful.[13] Despite their failure, these experiments were historically significant, since they were the first to establish the possibility of directly yoking human gas exchange to photosynthesis by a single species of plant—*Chlorella*. Somewhat later in the United States, the Boeing Corporation attempted to support human gas exchange for a period of 6–56 h.[14]

After the first unsuccessful experiments, scientists were pessimistic about the efficacy and feasibility of using bioregenerative systems on spacecraft. This skepticism was not surprising, since they had hoped to be immediately able to incorporate the results of their initial experiments in the design of spacecraft life support systems, and this was not possible. These negative conclusions were based on the results of the first essentially empirical period in the development of the BLSS and clearly resulted from direct attempts to create working models of systems without sufficient theoretical and experimental grounding. A contributing factor was the fact that the creation of the BLSS was understood from the very beginning as an applied or even an engineering problem, rather than as a component of the fundamental scientific problem of creating closed ecological systems, the underlying laws of which remain less well understood than those of natural ecosystems. To a significant extent, this discredited the area itself, and BLSS research was curtailed significantly and, subsequently continued only in the U.S.S.R.

The Russian portions of this chapter were translated into English by Lydia Razran Stone.

Many years of work were required to develop the theoretical and empirical rationale for the basic principles underlying the structural and functional organization of the BLSS; to identify ways to substantially increase the efficiency of algae in the system; and, especially, to create a completely new technology for their continuous cultivation. In addition, this technology had to be suitable for use, along with other components of the BLSS, including man, in a closed ecological system. Only after these problems were solved in the 1970s was it possible to return to experimental modeling of a man-rated BLSS. Experience with research on such models is described in Section IV.

The BLSS, as the term is currently understood, is designed to create and maintain a living environment for humans that is maximally appropriate to their needs, which are the products of evolution. Of course, this objective encompasses the traditional requirement for all life support systems (i.e., providing the major requirements for life—oxygen, water, and food), but it is not limited to them. The current concept of the future capabilities of the BLSS adds a completely new criterion—the goal of complete biological adequacy of the human living environment; and this goal cannot be achieved using nonbiological methods of life support.

The BLSS functions primarily through the utilization of a biological substance cycle created by the combined metabolic activity of plants; animals; micro-organisms; and humans themselves, who become an essential component of the system. These functions can be realized most fully through the use of biological structures characteristic of natural ecological systems—structures that have the properties of self-regulation; self-repair; adaptation; and, ultimately, the capacity for long-term autonomous survival in a state of stable equilibrium. These properties should serve as criteria for evaluating artificial ecosystems created as man-rated BLSSs.

Thus, we consider the BLSS as a kind of functional analog of natural ecosystems with respect to their organization, which is based on matter and energy linkages among individual functional components (subsystems) joined in a functionally integrated system. Individual BLSS subsystems are considered in Section II.

In the first edition of this work in 1975,[18] it was noted that, if a BLSS is conceived as an integrated biological system with a relatively closed biological substance cycle, it is easier to assess the potential for utilizing individual biological subsystems for regenerating certain substances in mixed biological-physical or biological-chemical systems. Today, we can point to the NASA CELSS Program, which is already conducting large-scale exploratory development and research and development on a component containing higher plants and other biological subjects in the non-biological LSS of Space Station. The CELSS Program is discussed in Section III.

In this chapter, in addition to presenting material directly relating to the BLSS, we also discuss new experimental data and ideas reflected in the recent scientific literature. One such idea is the general theory of habitability of extrabiospheric environments and, in particular, the significance of this concept for the development of man-rated life support systems that will support high levels of autonomy for space missions. This concept is discussed in section I. We also deem it essential to reconsider the biological effects of weightlessness from a broad ecological perspective, since BLSSs on spacecraft must function in microgravity. Weightlessness as a condition under which the BLSS is implemented is addressed in Section V.

Section VI describes mathematical modeling of biological systems.

The bulk of the material in this chapter was written by G.I. Meleshko and Ye.Ya. Shepelev (Institute of Biomedical Problems, Russian Federation Ministry of Health, Moscow). The material on the CELSS program was written by M.M. Averner (NASA, U.S.A.) and the section on mathematical modeling of BLSS was contributed by T. Volk of New York University (U.S.A.).

Fundamental Concepts and Terms

1) *Abiotic environment*: that part of an organism's living environment consisting of nonbiological factors.

2) *Autotrophs*: organisms capable of synthesizing organic substances from carbon dioxide, water, and mineral salts. On the basis of the energy source used in this process, autotrophs are subdivided into photoautotrophic organisms, which utilize the electromagnetic radiation of visible light; and chemoautotrophs, which obtain energy by oxidation of minerals, iron, sulphur, hydrogen, and nitrates.

3) *Biotic environment*: all the living elements of an organism's environment.

4) *Biomass*: the sum of all the substances comprising the body of an organism or set of organisms.

5) *Biosphere*: all portions of the lithosphere (solid envelope of the Earth), hydrosphere, and atmosphere linked (now or historically) with the activity of terrestrial organisms.

6) *Biocenosis*: functionally linked set (community) of organisms inhabiting a common territory or aquatic area.

7) *Biogeocenosis*: the biocenosis combined with the abiotic factors of the environment. This is the fundamental structural and functional subdivision (unit) of the biosphere that is responsible for a particular type of biogeochemical activity—the substance cycle.

8) *Heterotrophs*: organisms not capable of primary synthesis of organic substances and thus requiring the supply of such substances from without.

9) *Biological life support system*, or BLSS: "artificial" set of organisms and abiotic factors assembled in a limited territory. This system is a single functional community of autotrophs and heterotrophs, including humans, existing in a state of dynamic equilibrium within a relatively closed substance cycle regulated mainly by intrinsic control mechanisms.

10) *Population*: set of individuals of a single species inhabiting a relatively isolated homogeneous territory or aquatic area.

11) *Ecological system*: Unlike biogeocenosis (q.v.), which is defined as a unit of the biosphere, this term is applied to biological systems of any size—from the ocean to a particular puddle or from the forest to a stump. The absence of a size marker makes it possible to use the term more broadly than biogeocenosis, and it has been applied to the BLSS. However, this term refers only to biological systems and, in the ecological literature, is not used to refer to nonbiological systems.

12) *Closed ecological system*: hypothetical system based on a closed biological substance cycle without exchange of material beyond the enclosure of the system.

I. Biological Life Support Systems and Habitability

We have included this section in what might seem to be a narrowly specialized chapter on BLSS because creation of a life support system is often reduced to a set of purely technological (for physical-chemical systems) or biotechnological (for BLSS) problems, without considering the ecological problems associated with the major element of these systems—the human. Such ecological problems ultimately involve the theory of spacecraft habitability; i.e., the living conditions of the space crewmembers, who are the most important component of the life support systems being designed.

Any BLSS concept is derived from current ideas about the living environment humans need and the concept of habitability that underlies these ideas. As we are on the threshold of a new phase of manned space flight, it would be useful to consider an issue that, at first, might seem to be obvious; i.e., the purpose and specifications of man-rated life support systems. Each time such a system is designed, specifications are derived from current ideas about the necessary and sufficient conditions and components of a living environment as applied to specific space programs. However, these ideas inevitably change over time, as the duration and autonomy of space missions increase and as our understanding of the human living environment deepens.

If we base our concept of habitability solely on the standard list of physical and hygienic requirements for life, then it is sufficient to consider the following as goals of a life support system: to support certain physical-chemical parameters of the environment; to provide certain amounts of consumable substances (oxygen, water, and food); and to dispose of waste products for a certain period of time. However, if we base our concept of habitability on the requirement for a biologically complete environment, one that will not, in principle, curtail the life span of a human living in it, then the life support system must meet ecological requirements derived from this requirement. Such an environment must meet the needs developed by humans over the course of evolution (which are still not thoroughly understood) and share the major properties of the natural environment. The only life support system that can meet these needs is one based on a biological substance cycle, which is the only validated mechanism on our planet for sustaining life over a prolonged period of time.

We have failed to find in the literature a comprehensive discussion of the current tacit understanding of the concept of habitability. It is possible that there is no such understanding and that, in its stead, we have empirical practice. There is also no unambiguous generally accepted definition of the term "habitability" itself. It seems possible to define "habitability" as the totality of environmental conditions (physical, chemical, biological, and social) that make the environment suitable for human survival and activity, either indefinitely or for a specific, limited period of time (limited habitability). Obviously, at the current stage of manned space flight, we are dealing with limited habitability. Our definition of habitability is future oriented: the future goal of space medicine is implicit in it—to decrease constraints on the period of time that humans can remain in space (of course, without ill effects), and to transform the limited habitability of current spacecraft into unlimited, true habitability. From this point of view, our strategy in the medical support of future space programs must involve determining what level of inadequacy is acceptable for an artificial spacecraft environment (as compared to the natural environment on Earth).

In the U.S.S.R., we have been working on certain aspects of the ecological concept of habitability and its initial assumptions for a long time. This work is described in a number of sources.[15–19] In its most general form, it is presented in a paper by O.G. Gazenko, A.I. Grigoryev, et al.[20]

The major aspect of the ecological concept of habitability is the biological completeness of the living environment. The concept of biological completeness (i.e., the full adequacy of the living environment to meet the evolved needs of humans) developed gradually. It was derived from a number of sources as we became increasingly aware of the advantages of conceiving of nature as an integral whole and began to recognize the power implicit in the principle of the organism's unity with its environment. It is interesting that the most profound treatment of this principle is encountered outside of biology, in the ideas of the geologist and chemist, V.I. Vernadskiy,[21] who considered the unity of the organism-environment system not merely in the context of individual organisms but on a global scale.

The concept of the biological completeness of the environment was first advanced with regard to the environment of the roots of plants in a discussion of the possibility of directly utilizing the products of physical-chemical mineralization of organic wastes in artificial ecological systems.[9] This idea was derived from the notion of the soil as a complex natural body in which the destruction of organic substances occurs simultaneously with soil-transforming processes involving many soil organisms and root systems. As a result of this process, plants obtain not only the mineral substances known in agrochemistry but also a whole set of physical, mineral, organic, and biological environmental components maximally suited to the linkages and needs developed through evolution. The biological completeness of the environment is a direct consequence of its natural, biogenic origin. Thus, the introduction of the physical-chemical mineralization of organic wastes into a biological substance cycle, or the use of hydroponics to cultivate plants in a BLSS, cannot qualify as adequate, since they fail to supply a biologically complete environment to the roots of the plant.

Later, the concept of biological completeness was derived independently in hydrobiology with regard to drinking water. Here, biological completeness can be defined as the capacity to serve as the living environment of aquatic organisms and is a consequence of the fact that natural bodies of water contain the biologically active primary and secondary by-products of the vital functions of hydrobionts.[22] Here, too, the biological completeness of the environment is associated with its biogenic origin. It is obvious that, *a priori*, water regenerated by physical-chemical methods cannot possess this fundamental property of naturally occurring water. As we will argue below, such artificially reclaimed water does not possess the properties of a biologically complete living environment for aquatic organisms.

Everything that was said with regard to soil and water can be logically extended to the general concept of biological completeness of any natural environment to the organisms that inhabit it. In essence, this is an *a priori* property of the natural environment and does not require further empirical proof. The completeness of the natural environment follows from the long period of joint evolution of terrestrial organisms and the biosphere in the presence of the Earth's geophysical fields. At each moment during the evolution of the biosphere, terrestrial organisms manifested the maximum attainable level of adaptation to their environment and to assimilation of available material and energy resources, and there existed the maximum possible number of energy, trophic, and signal (informational) linkages between the organism and its environment. Taken as a whole, this situation also defines the concept of the biological completeness of the living environment. Of course, all this applies to humans as well, regardless of their ability to optimize their individual physical environments with the help of shelter, clothing, etc.

Thus, biological completeness of the environment may be defined as the extent to which the environment meets the evolved needs of an organism, enabling the organism to survive for an unlimited time in this environment. We apply this concept both to the environment as a whole and to its major components—the natural atmosphere, natural water, and soil and also to the size and configuration of the living environment (a "social" factor of varying importance for different organisms). The key feature of this definition (as is the case for the definition of the concept of habitability described above) is that there is no time limit on habitation. This is a critical point for the development of future BLSSs, in which habitation may continue over a number of natural generations. An axiom can be derived here: The standard for biological completeness against which every artificially generated living environment must be evaluated is the natural environment and its most important components—the atmosphere, water, and soil (as the environment of plants and the locus of interactions between biotic and abiotic elements).

Table 1 Critical period for onset of deprivation effects for a number of environmental factors

Factor	Critical time
Oxygen	$n \cdot 10^{-2}$(min)
Water	$n \cdot 10^{1}$ (days)
Food	$n \cdot 10^{2}$ (weeks)
Vitamins, minerals	$n \cdot 10^{3}$ (months, year)
????	$n \cdot 10^{m}$ ($m \geq 4$) (years, generations)

The importance of applying the appropriate concept of habitability to the development of life support systems should become particularly obvious in the near future, when we will be preparing for such inevitable space programs as interplanetary flights and planetary bases. Such programs will compel humans to spend many years cut off from contact with the Earth's biosphere. Under these conditions, an appropriate understanding of the concept of habitability may turn out to be decisive with respect to the biomedical reliability of the space programs themselves. We are approaching an era when concepts from theoretical biology and even natural philosophy must become organizing factors in the development of far-reaching programs of human extraterrestrial activity. To put it simply, when scientists and managers plan programs that require humans to live and work away from the Earth, they must clearly understand the factors of which these humans will be deprived and what the consequences will be.

Although habitability has not been formally defined, the operational definition in use today may be inferred from the fact that the standards for ambient conditions on manned spacecraft are based on traditional physiological and hygienic requirements for such an environment. The current implicit definition of the concept of habitability encompasses a limited number of natural factors that are of critical importance for life support. The most important of these factors are presented in Table 1, in which we have attempted to compare incommensurate environmental factors by citing the time that must elapse before adverse consequences of disrupted human-environment linkages manifest themselves.

The broken line in this table marks the bounds of our knowledge of the major environmental factors critical to human survival. This knowledge underlies the way in which standards are set for living conditions in inhabited spacecraft.

The upper portion of Table 1 contains only factors the deprivation of which leads to critical problems for humans that become manifest in 1 year or less; i.e., approximately 2 percent of the length of a generation or less than 5 percent of the working life of a cosmonaut. However, this does not mean that no other environmental factors are critical to human life with deprivation effects that become manifest only after more than a year, within a single generation, or even in subsequent generations.

Potential factors of this sort that today are not considered in habitability include geophysical fields—magnetic, gravitational, and electrical; the constant generation and motion of atmospheric charged particles of various origins (aero-ions) associated with the Earth's electrical field; aerosol particles, including bacteria, spores, and plant pollen; and ultraviolet radiation and its associated photochemical activity.

Furthermore, the current understanding of the environment still does not encompass its most important characteristic from the standpoint of the theory of habitability—the biogenic essence of the natural environment. After all, the natural atmosphere is qualitatively very different from our models of the "space atmosphere" (nitrogen + oxygen + carbon dioxide), whereas natural water is far from being merely a substance with the chemical formula H_2O (which, incidentally, in its pure form is harmful to all living things).

Science, of course, does have some understanding of many factors not covered in the table, but this knowledge falls within the purview of a number of separate disciplines (i.e., atmospheric physics and chemistry, hydrology, hydrobiology, ecological physiology, medical geography, and health resort science) and has not been integrated into a unified body of knowledge concerning the natural factors of the human environment, a science of terrestrial human ecology. This is a significant problem for the development of our future concepts of habitability and human ecology.

It is well known that the normal components of the Earth's atmosphere include hundreds of organic substances, mainly released by plants and soil micro-organisms. In traditional toxicology, these are usually called "harmful contaminants." Typically, no one even considers whether any of these permanent components of the atmosphere may be beneficial or even essential to humans. This is true of every discipline except health resort science, the science of natural therapeutic factors. As early as the 1920s, N.G. Kholodnyy[23] began to work actively on this problem. He hypothesized that the volatile substances released by plants are physiologically active and serve vitamin-like functions essential for normal vital activity when inhaled by humans or animals. He proposed that they be called "atmovitamins," or respiratory vitamins. Here, we have an example of an idea that was ahead of its time and is acquiring new prestige only today, not merely within the study of human terrestrial ecology but also in human space ecology as it pertains to the BLSS. Any program that develops our future concept of habitability for extrabiospheric manned spacecraft intended for multiyear autonomous habitation should encompass the further development of this idea.

Aside from gaseous components, the Earth's atmosphere contains a large number of aerosols and multimolecular compounds, which are organic as well as inorganic in nature. Aerosol particles have diameters ranging from submicrons to microns. In the submicron range, these particles have been shown to be associated with changes in the physical properties of the major components of the atmosphere and increases in their chemical and catalytic activity.[24] If such particles are ionized in the Earth's electrical field, then they become aero-

Table 2 Amount (in tons/year) of products of certain mass-exchange processes emitted into the biosphere[25]

Substance	Amount emitted into atmosphere, tons/year
Vapors from natural or man-made aerosol-forming substances	1×10^9
Ions emitted with transpirational water of plants	1.2 to 1.4×10^9
Spores and plant pollen	1.6×10^9
Volcanic emissions into the atmosphere	2.3 to 3×10^9

ions—an independent and active ecological factor in the living environment of terrestrial organisms. The absolute quantities of biogenic and abiogenic emissions of a number of substances in the atmosphere are given in Table 2.[25]

It will be noted that the amounts of substances emitted as a result of a number heterogeneous processes are surprisingly similar. Only global processes (i.e., the production of plant biomass and oxygen) release orders of magnitude more substances into the atmosphere, with emissions reaching 2.32×10^{11} metric tons/year.[26]

Air is the single component of the Earth's natural environment with which living things are in contact every second of their lives. This is not true of either water or food. The fact that, in a year, approximately 5000 m^3 of air pass through the lungs provides some idea of the magnitude of the flow of various organic and mineral components of the atmosphere through the human body. Currently, science does not have even an approximate estimate of the true ecological significance to humans of these permanent components of the natural atmosphere. Space medicine has devoted even less attention to this issue.

Thus, even a superficial review of findings concerning the physical, chemical, and biological components of the natural atmosphere does more than merely demonstrate the complexity of its composition. It is completely obvious that the pathways of many of the biosphere's biological and geochemical cycles (and, thus, the interactions among various terrestrial forms of life, including humans) cross and recross in the biosphere. This, alone, is enough to demonstrate that the traditional substitution of a mere mixture of nitrogen, oxygen, and carbon dioxide for the Earth's natural atmosphere on manned spacecraft is only an interim solution. Such a substitution cannot be relied upon in future space programs involving interplanetary flights, in which human contact with the biosphere will be severed for a number of years. In science, which has become so compartmentalized, there is currently a trend to return to earlier, more holistic ideas of nature as a unified entity. In this context it is extremely appropriate to resurrect the old-fashioned but profound idea that what humans breathe is air and not the oxygen that science puts such faith in today.

Natural water is also a complex substance with many components. All the forms that it takes on the Earth are, or have been, the living environment of a variety of organisms, and many of its properties are associated with living matter. Water regenerated from various substances by means of various physical-chemical methods, even when it fully meets standards for potable water, cannot support aquatic organisms.[27] For this reason, scientists concerned with hydrobiology were long ago forced to formulate the concept of biologically complete water, which they identified with the presence of metabolic products of aquatic organisms (lipids, free fatty acids, products of lipid peroxidation, fat-soluble vitamins, free radicals, etc.). Most of the results in this area were obtained by hydrobiologists at Moscow State University.

All of this demonstrates that the environments we have been creating on spacecraft are, unfortunately, only surrogates for the natural environment. It shows the extreme complexity of the composition and origin (biogenic and abiogenic) of the natural atmosphere and natural water and how inextricably related they are to the vital activity of the organisms that inhabit them.

It is obvious that on Earth there are no alternative, nonbiological mechanisms that could reproduce the natural environment in all its biological richness. It is also obvious that, like all other living things, humans are, in principle, unable to live in an artificial, abiogenic environment for longer than the limited period made possible by the inertia of biological systems. This assertion does not require empirical verification, since it follows logically from the fact that living things evolved by adapting to their environment. The requisite proof was long ago furnished by the history of the biosphere and the entire history of the development of humans as components and products of the biosphere. The entire history of the development and evolutionary consolidation of the unity of life and its environment has served as a continuous "experiment" in the actual, scientific, and not merely philosophical sense of the term. Recognition of the practical constructive power of this principle of unity and acknowledgement of the place of human beings as components and products of nature on the Earth must form the basis for deriving the fundamental principle underlying modern human ecology and the concept of habitability associated with it.

These ideas about the natural environment and the place of human beings within it have enabled us to derive the following empirical propositions that may be used as the axiomatic basis for deriving future concepts of habitability, given the new conditions under which this concept must be applied—the severance of human contact with the biosphere for a number of years.[20]

1) Our knowledge of the natural environment of humans is inadequate. It does not include the full set of the environment's properties as a complex, multicomponent, biogenic, self-regulating, and self-repairing system.

2) The natural environment has been the arena of the adaptive evolution of life on Earth. This fact establishes its *a priori* adequacy to meet the needs of living things (which developed through evolution) and distinguishes it in principle from any artificial, abiogenic environment.

3) The natural environment of the Earth is the only one that has been evolutionarily tested and demonstrated to be suitable *a priori* for the unlimited long-term survival of humans. No possible abiogenic version has this sort of *a priori* validity. For this reason, the natural environment must serve as the absolute standard for a living environment for humans, as well as other living things.

4) The duration of human habitation of any artificial, abiogenic environment is theoretically limited; the greater the lack of correspondence between this environment and its natural prototype, the greater are these limits.

5) The manned spacecraft environment can be made biologically complete only if it has been formed through biological mechanisms analogous to those through which natural ecosystems are formed.

For a long time to come, the quality of life and the complete satisfaction of human needs on space stations will continue to depend on the limited capacities of space technology; space medicine, therefore, will have to accept the reality that technological considerations have first priority. But this reality is, in principle, temporary. The inevitable increase in the technological capacities (including power supplies) of spacecraft will diminish the attention that must be paid to technological limitations, and the emphasis that can be placed on human needs and requirements will gradually increase. At the same time, the issue of habitability will be extended to encompass an increasing number of properties of humans themselves, as well as their living environment.

For the present, one thing is clear: It is theoretically possible for humans to live and work in space for an arbitrarily long period of time. In principle, the duration of severance of human contact with the Earth may be increased in direct proportion to how representative a subset of human biospheric linkages have been incorporated into the actual BLSS. In this chapter, however, we do not touch on the biosocial and psychosocial aspects of the problem, which will become increasingly significant with increasing duration of isolation from the Earth. These aspects require a separate analysis.

II. Structural and Functional Organization of the Biological Life Support System

An ecological approach to development of the BLSS dictates that the functional structure of the system developed should be based on the structure of natural ecosystems. Figure 1 presents a model of the trophic linkages among the major components of an ecological system, showing its various trophic levels. The first level comprises the "energy gates" of the system, through which energy enters from without. This provides the basis for the existence of the entire system. This level is formed of photoautotrophic organisms, which reproduce their mass from inorganic substances (e.g., water, carbon dioxide, and minerals), utilizing the electromagnetic energy of light. The second level comprises herbivorous animals, which, in turn, serve as food for the carnivorous animals (primary, secondary, etc.) that form the third and subse-

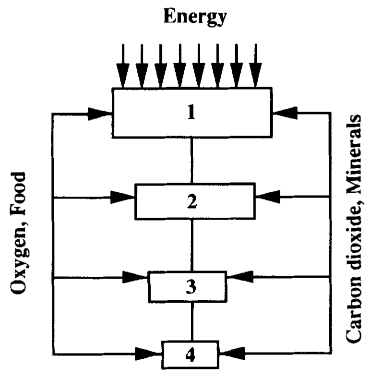


Fig. 1 Trophic linkages in an ecological system.

quent trophic levels, the number of which depends on the length of a specific food chain.

Typically, many competing or complementary species occupy each trophic level. Ultimately, the last stage of the trophic chain comprises various soil organisms (invertebrates, fungi, protozoa, and bacteria), which complete the decomposition of organic substances and transform them into the mineral compounds that are used by plants in the next cycle of synthesis of organic substances and accumulation of energy. The passage of substances from one trophic level to the next entails loss of a significant amount of energy; Fig. 1 depicts this passage by a progressive decrease in the area of the rectangles representing the various trophic levels.

In an actual BLSS, photoautotrophic organisms may be represented by higher plants and one-celled algae. The next trophic level, that of heterotrophic organisms, comprises humans and those herbivorous animals that can be a source of human food. The final stage of mineralization and return of unused organic substances and wastes to the system is realized by heterotrophic micro-organisms, which perform this function in a community with algae and higher plants or in special microbiological reactors. All these structural subsystems of the BLSS are called the functional components of the BLSS. Such components can be defined as relatively isolated populations or communities of organisms realizing a particular stage in the substance cycle of the system.

A. Photoautotrophic Component

The key process of synthesizing organic substances by using light energy occurs at this level. In its general form, this occurs in accordance with the formula

$$nCO_2 + nH_2O \longrightarrow n(CH_2O) + nO_2$$

Absorbing light energy, in the form of the chemical bond energy of organic substances, is expended in the subsequent trophic chains of the system. This formula depicts the biological regeneration of the atmosphere—replenishment of oxygen and elimination of excess carbon dioxide—through photosynthesis. Only a small portion of the spectrum of light radiation (the 380–710-nm waveband) can be used by plants for photosynthesis. This waveband is called photosynthetically active radiation (PAR).

The light energy that is bound in organic substances may, in theory, reach 20 percent of that absorbed by the plants, and this value is used as an indicator of the energy efficiency of photosynthesis. Under actual conditions, this value is significantly lower. For one-celled algae in the laboratory, it fluctuates within the range of 7–12 percent. In higher plants, efficiency is 0.2–1.5 percent under natural conditions and reaches 4–14 per cent under laboratory conditions.

The photosynthetic component not only provides the basis for the existence of the BLSS but also determines its overall structure and functional capacities. If it is based on one-celled algae alone, the BLSS fully solves the problems of regenerating the atmosphere and water and stabilizing organic components and atmospheric microflora; however, it produces only a small fraction of the food required. Under these conditions, the photosynthetic component has minimal mass and volume. If this component consists exclusively of higher plants, then it is capable of producing the requisite amount of food but has less influence on the atmosphere. In addition, a photosynthetic component consisting of higher plants would have to have high mass and would occupy considerable space. Of course, in developing the actual BLSS, we may consider the advantages and shortcomings of each of these particular photosynthetic components and choose to combine them in order to optimize the human living environment, given the limitations of space technology.

1. Higher Plants

Higher plants will probably compose the major portion of the photoautotrophic component in a man-rated BLSS. Aside from regenerating the atmosphere, higher plants provide the vegetable component of the diet. The diverse nutritional requirements of the human diet ordinarily satisfied by vegetables are not readily satisfied by any other source on spacecraft. Since BLSS began to be considered, the issue of proper criteria for selecting plant and animal species for a BLSS has been discussed repeatedly in the literature. This question is typically formulated in terms of absolute criteria, which are not ranked for importance and are meant to apply to any BLSS, regardless of purpose. The main criteria cited are high productivity per unit weight, high efficiency of energy use, maximum proportion of edible biomass, compatibility with other BLSS components and humans, adaptability to cultivation under conditions imposed by space flight, and stability under exposure to extreme environmental factors.

The most general criteria for selecting plants for space greenhouses are cited in Hoff et al.,[28] with each plant species assigned an overall numerical rating, which is important for

Table 3 Two variants of crops proposed for space greenhouses
[From Ashida et al.[30] and Midorikawa et al.[31]]

Culture	Specific area of the crop, m^2/man	
	Ashida et al.	Midorikawa et al.
Rice	16.5	18.8
Wheat	19.25	–
Potatoes	5.5	–
Sweet potatoes	5.5	–
Sugar beets	2.75	–
Lettuce	2.75	1.8
Tomatoes	2.75	–
Peanuts	2.75	–
Soybeans	2.75	16.6
Strawberries	–	1.3

estimating the intrasystemic efficiency of the higher plant component. Similar data are also provided in a paper by F. Salisbury.[29] Current ideas about what plant species should be selected for space greenhouses vary with regard to the variety of nutrients they provide for the human diet, as is illustrated in Table 3.[30,31]

Column 2 of this table is of particular interest here. The assumption is made in this work that a necessary and sufficient human diet (2940 kcal per day, according to the authors' data[31]) can be provided primarily by rice and soybeans. Although the adequacy of this particular diet is doubtful, this work does implicitly raise the possibility of a vegetarian diet (as does the other work incorporated in this table) and, thus, provides the impetus for an open scientific discussion of this issue.

The issue can be reduced to the following question: Is there some essential minimum of "animal products" that must be included in the daily human diet, and, if so, what is this minimum? Space medicine has not yet considered this issue and, thus, can provide no answers, even with respect to traditional animal foods. How does science evaluate nontraditional animal products, starting with the biomass of plankton, including infusoria? Does the concept "products of animal origin" (apart from the vagueness of the term "origin") have any real biological (including biochemical) significance? After all, vegetarianism has been flourishing for centuries.

Today, these questions have moved from the purely theoretical realm and become practical interests of space medicine, since they relate directly to the structure and functions of the BLSS. The question of the necessary percentage of animal products (even traditional animal products) in the human diet has no definite, scientifically based answer. At the same time, it is well known that decreasing the proportion of the heterotrophic component of the ecosystem (BLSS) increases its energy efficiency and, thus, is preferable from this standpoint. This problem must be addressed by space biology and medicine to support future space programs.

Since mission volume, mass, and energy are always limited, the foremost factors in selecting particular plants for the BLSS are their production of edible biomass per unit volume and mass, requirements for light energy, nutritional value, and duration of growth cycle. For this reason, most early investigations concentrated on achieving maximum increases in productivity of particular cultures. NASA CELSS studies addressed conditions for obtaining the maximum yield of wheat through increases in the density of planting, intensity and duration of illumination, temperature, levels of carbon dioxide and humidity, and feeding with a nutrient solution. Calculations have shown that the mass and dimensions of the system were more limiting than energy. Thus, it was decided to attempt to obtain maximum yields per unit space per unit time, even if this meant lowering the efficiency of light use, which is unavoidable for high intensities.[32]

Using this approach, with illumination at the level of atmospheric sunlight (2 cal/m^2/min total radiation), the maximum acceptable density of planting, the maximum level of carbon dioxide compatible with human needs, and optimal ambient conditions (temperature and humidity), Bugbee and Salisbury[32] obtained a yield of short-stem wheat of up to 60 grams/m^2/day, which exceeds record agricultural yields by a factor of 4. The harvest index (percentage of edible biomass in the total yield) was approximately 45 percent.

These experimenters believe that the productivity of wheat may approach that of one-celled algae; however, attainment of an analogous yield of rice and soybeans would undoubtedly be more difficult. Rice and soybeans are short-day plants and require a long period of darkness, which decreases the daily amount of radiation absorbed and the rate of growth.

The issue of the area (and, indirectly, the volume) required for the plants in a space greenhouse is extremely important for a BLSS and is a function of the plants' productivity. For example, given the productivity of wheat of 60 grams/m^2/day obtained under laboratory conditions by Bugbee and Salisbury,[32] 13 m^2 of sown area are sufficient for one person. For a lunar base, considering the duration of solar illumination on the surface of the Moon, the area required is estimated at 40–50 m^2 per person.

It should be noted that none of these theoretical calculations consider experience in growing plants, including wheat, as a component of truly closed systems. Experience has shown that, under such conditions, it is not always possible to obtain yields analogous to those obtained under open cultivation conditions.[33,34] The reasons for this are still unclear and require careful study, since they may make it difficult or impossible to implement certain designs. It is important that these considerations apply not so much to total biomass as to the specialized plant organs producing edible biomass, such as edible roots and especially reproductive organs (grains and oil-bearing crops). The course of plant morphogenesis and embryogenesis under different ambient physical conditions, in closed ecosystems with close interaction of all BLSS components in an extremely limited space, tends to reveal the incompleteness of our understanding of these complex processes and functions. In any event, in the BLSS models we have studied,[34] we observed occasional periods during which grain failed to form in wheat plants. This failure had no obvious relationship to other components of the system or cultivation conditions.

Plant cultivation methods remain an important problem for a BLSS. It has been established indirectly that the best methods are hydroponics, which permit strict control of the delivery of minerals to plants, and even aeroponics, which minimize the amount of nutrient solution. In this connection, F. Salisbury's statement to the effect that, given efficient hydroponics, the root system of the plant comprises a total of 3–4 percent of the total dry biomass, compared to 30–40 percent in a plant growing in soil,[29] is of interest. However, the difficulty of using free liquids in weightlessness compels consideration of substrate methods of cultivation, using salt-saturated substrates of artificial (ion exchange resins) or natural origins. A natural salt-saturated substrate (natural zeolite) was used in the Soviet space greenhouse flown on Mir starting in June 1990.

The unique conditions associated with the construction of lunar and planetary bases also suggest that substrate methods may be the most promising. If it is possible to reproduce the natural process of soil formation to create fertile soil on the Moon and other planets by analogy to the soil formation process on the ancient Earth, the planet's own soil could be used for plant cultivation. At the Institute of Biomedical Problems in Moscow, this possibility was subjected to experimental testing in a 3-year (1981–1983) experiment involving systematic introduction of wheat straw into an inert substrate containing 10 percent natural straw by weight, using humus in a hotbed as a control. It was found that a stable soil biocomplex formed in the inert substrate during the first year. After this period, the total dry mass of the substrate did not increase; and the rate of decay of straw corresponded to the rate of its introduction into the substrate, as well as to the rate of formation in a greenhouse of comparable area. The level of organic substance in the newly formed soil stabilized at a level of approximately 6 percent of the total dry mass of the substrate.[35]

This process would appear to be the most natural route for processing and utilizing any other organic wastes in the BLSS, involving not only soil microflora but also substances emitted by the roots. Processes of mineralization of organic substances are accompanied by processes of secondary biosynthesis of complex humic compounds, the importance of which (for soil fertility) have long been recognized. This natural combination of biological mineralization and utilization of natural wastes in the area of the root, with formation of biologically complete substrates, approximates a functional analog of natural soil. This is fully consistent with the concept of the biological completeness of the living environment in the BLSS—in this case, the living environment of plants.

With all its advantages, a photoautotrophic component based solely on higher plants has an important shortcoming—the high inertia associated with the long cycle of plant development, which, as a rule, exceeds 30 days. This means that a long period is required to restore the normal functioning of the higher plant component if it is damaged in an emergency or accident. Moreover, the total gas exchange ratio of higher plants (CO_2:O_2), is close to 1 and, therefore, is nowhere near the respiratory quotient of humans, giving rise to the problems of excess oxygen and carbon dioxide deficit.

2. One-Celled Algae

In a closed-substance-cycle system, algae fulfill the same air revitalization function as higher plants, enabling energy to enter the system from without. Of greatest interest for closed ecological systems are green and blue-green, one-celled algae (cyanobacteria). The small size of the individual cells, their relatively simple morphology, high rate of reproduction, short developmental cycle, high level of photosynthesis per unit of biomass, and high stability under exposure to adverse environmental factors work together to enable intense cultivation with automatic stabilization of ambient conditions. The algae that have been studied most often are those of the *Chlorella* family. This species was the first candidate for a photosynthetic (photoautotrophic) component of a BLSS, and its use for this purpose was widely discussed in the literature as early as the 1950s. The Institute of Biomedical Problems constructed the first models of biological atmosphere regeneration systems using *Chlorella*.[13] Subsequently, a functional component of a closed-substance-cycle system using *Chlorella* was developed. Scientists derived principles for obtaining high productivity and developed a technology involving continuous cultivation with a closed cycle of nutrient medium balanced for utilization of mineral elements by cells. This is the only possible method for closed-substance-cycle systems. This technology provided optimal conditions for the formation of a stable bacterial community concomitant with the algae and maintained the stability of the nonsterile algae culture as an algo-bacterial cenosis. The first experimental models of a man-rated BLSS had this system as a component and demonstrated the capacity of algae in a community with bacteria to play a number of unanticipated roles in generating a living environment suitable for humans.

An in-depth study of BLSS models based on photosynthesis by one-celled algae (*Chlorella*) has shown that the traditional comparison of one-celled algae and higher plants using physiological and technological criteria is insufficient for determining their roles and functions in a man-rated BLSS as a closed ecosystem. Additional ecological criteria are required. Using these criteria, it was found that, within the BLSS models studied, an "algae culture" is not actually a "culture" (as, for example, wheat) but is a relatively independent autotrophic-heterotrophic aqueous ecosystem with concomitant heterotrophic microflora composing an integral part. This is why system models based on *Chlorella* remained stable

Table 4 Composition of the biomass (percent of dry weight) of various species of one-celled algae

Type of algae	Protein	Fat	Carbohydrate	Ash
Chlorella	53.2	20.7	19.1	5.7
Chlamydomonas	34.1	8.8	54.5	4.5
Closteriopsis	34.3	16.9	46.2	4.6
Euglena	56.0	22.0	18.2	4.5
Spirulina	57.5	12.0	22.5	7.8

over time and, in addition to playing their assigned roles of regenerating air and water, also significantly increased levels of organic, bacterial, aero-ion, and aerosol components in the atmosphere. In other systems, functions such as these must be performed by special devices. The weight, volume, and power requirements of these devices are typically not counted in comparative evaluations, which is a mistake.

The major shortcoming of BLSS models based on *Chlorella* photosynthesis is the low closure of trophic linkages in the system. The biomass synthesized by *Chlorella*, despite its high caloric value, cannot serve as a major component of the human diet, as was proposed very early in work on this problem. In the system models that have been created, this biomass has been used in the diet in only small quantities, about 10 percent of the total weight of the diet. This is because the cell walls of *Chlorella* cells resist decomposition and the biomass contains high levels of protein and nucleic acids and low levels of carbohydrates. However, there are ways to optimize the composition of the biomass and increase its proportion in the human diet. This may be accomplished by including in this component other forms of one-celled algae with biomass composition different from that of *Chlorella*.

Various forms of algae with biomass composition differing from that of *Chlorella* have been studied at the Institute for Biomedical Problems (see Table 4). By selecting a community of algae having biomass with different compositions, it is possible to attain a more optimal overall biomass (with respect to the composition of the diet) and, thus, to increase the closure of the trophic linkages in models of this type (i.e., those without animals). However, the issue of the food value of algae and their possible use in the human diet cannot be considered entirely closed, despite a substantial amount of research in Japan, the United States, and the U.S.S.R.

Higher plants must comprise the major portion of the photoautrotrophic component with respect to the amount of participation in the total substance cycle. However, the inclusion of one-celled algae significantly improves performance with respect to biomass composition, as well as enhances the dynamic properties of the system. One-celled algae, because of their high reproduction rate and the relative simplicity of the technology for growing them, are the least inert component in the system for regulating the photoautotrophic component and increasing its "repairability" after emergencies have damaged it. Since inclusion of one-celled algae is the most feasible way to maintain the productivity of the photoautotrophic component (e.g., with respect to gas exchange) within the required range of values, the minimum proportion of algae used in this component should be that required to perform this function. The maximum proportion of one-celled algae in the photoautotrophic component will evidently be determined by the extent to which their biomass can be used in the diet of humans and animals.

B. Heterotrophic Component

In the first, necessarily simplified BLSS variants, the major function of the heterotrophic component, as the metabolic complement of plants, was performed by humans. However, the diet of these humans required the inclusion of other heterotrophs to produce animal protein. Animals selected for a BLSS have to meet the generally accepted criteria of high productivity per unit weight, energy efficiency, minimal proportion of nonusable biomass, etc. However, there are also special system requirements—minimal food competition with humans and maximal ability to consume plant wastes inedible by humans. In general, the preferable species are those whose own weight is low, both because of the high specific metabolic rate of smaller species and the fact that, because of the large number of individuals in the population, the function of the component as a whole is not severely disrupted by the accidental death of a few individuals.

The range of choice of species for the heterotrophic component is very great and, in principle, encompasses the entire animal kingdom, from protozoa to mammals. One of the first overviews of this subject, performed by Yazdovskiy and Ratner[36] covered almost this entire range. Serious consideration of fish in this role[37,38] has typically led to their rejection on the grounds of the great weight of the water required to maintain them. However, if we consider the need for some amount of shock-absorbing substances in the major flows of the cycle, then the use of such amounts of water can only be considered beneficial to the system.

With respect to invertebrates, the Institute of Biomedical Problems investigated the physiological and ecological characteristics of slugs for use in a BLSS. The proportion of edible biomass reached 75 percent, while the protein level approached 50 percent. These parameters are substantially higher than those for traditional agricultural animals and are of interest for future variants of the BLSS.[39]

At present, development of the heterotrophic component is at the stage of theoretical consideration and ground-based experimentation. The first attempts to study the issue of raising food animals under actual space-flight conditions revealed unique and unforeseen problems associated with weightlessness, problems which are more difficult to solve for animals than for humans.

Scientists at the Institute of Biomedical Problems (Moscow), in collaboration with specialists from Czechoslovakia, investigated the use of birds in a BLSS not only as a direct source of food but also to produce secondary food products—eggs. The results of experiments on Mir showed that for this highly organized free-living species, new problems associated with motor behavior arose in weightlessness.[40] In the absence of gravity, the whole set of innate sensorimotor reflexes and individual "skills" developed under terrestrial conditions becomes inappropriate. This poses new problems in the technology of animal maintenance in weightlessness—restraint in space, feeding, breeding, and others—complicating the issue considerably. This suggests a new, unexpected criterion for selecting animals for a BLSS: their constant association with a substrate in order to eliminate the problems of orientation and motor behavior in microgravity.

These first orbital experiments showed that developing a heterotrophic BLSS component using traditional agricultural animals and birds may be far more complex, even immeasurably more complex, than developing a component using nontraditional sources of animal products.

C. Organic Waste Processing Component

Major sources of waste in a BLSS are humans and the photoautotrophic component, which produces a significant proportion of the inedible biomass. The function of the organic waste processing subsystem of the BLSS is to decompose this waste and return the waste substances to the overall cycle through the photoautotrophic component. Inedible plant biomass, cooking wastes, fecal matter, and liquid wastes in the form of wash water and urine, comprise the bulk of such wastes. As the heterogeneity of species increases and the structure of the higher plant component approaches that of the human diet, the absolute and relative amounts of inedible biomass can only increase. This essentially makes the system an open one; and, if all the biomass is not returned to the cycle, then equivalent supplies of carbon dioxide and water have to be provided to compensate for losses of carbon dioxide, oxygen, and hydrogen.

The development of this component of the BLSS has not advanced significantly since the publication of the first edition of this work. As was the case then, we are concentrating on the processes of bacterial decomposition of organic wastes in aerobic conditions in special fermenters, with emission of carbon dioxide and water and subsequent utilization of some mixture of the products of decay by higher plants. However, this method has still not advanced beyond the stage of exploration in ground-based experiments; and, more important, the compatibility of higher plants with this component for processing wastes, as well as the products thus produced, has not been studied under closed conditions.

The only new approach to this problem noted here is the attempt to provide bacterial decomposition of plant wastes right in the substrate, with the plants themselves participating in the process in an analog of natural soil processes. This was described above in the section on higher plants.[35]

During the earliest period of work on BLSSs, in the 1960s, the idea arose that the final stages of the cycle (i.e., the transformation of organic substances by mineralizing organisms) could be replaced by physical-chemical processes for decomposing organic substances. At that time, conditions of high-temperature incineration, catalytic oxidation in a liquid environment, and "wet oxidation" at high temperatures and pressures began to be intensively studied. It became clear that decomposition and mineralization of organic substances into component elements and their oxides would make them difficult to utilize by the higher plant component; i.e., to return them to the cycle. This pertained especially to the major biogenic elements, phosphorus and sulphur, which are lost in the form of oxides during incineration in the gas phase and to nitrogen generated in its free state, a form which could not be assimilated by plants. A number of oxides of ash elements are relatively insoluble.

Nevertheless, in the United States and Japan, interest in these processes has recently revived in connection with the CELSS Program. Takahashi[41] describes a method of wet oxidation of wastes at a temperature as high as 700 °C and a pressure as great as 250 atm. However, this work gives no indication that the products obtained were used by higher plants.

While on the subject of the potential use of physical-chemical decomposition of organic wastes in BLSS, we should note that these processes are not functionally equivalent to the natural processes of biological decomposition of organic substances in nature, particularly in the soil. Biological decomposition in the soil results from the combined and interrelated activity of soil organisms and substances emitted by plant roots to produce products appropriate to the trophic needs of plants and to synthesize humus, which supports the natural fertility of plants. This is the way nature solves the problem of integrating the processes of mineralization and utilization of organic wastes in terrestrial and aquatic ecosystems. This is also precisely how we solved the problem of mineralization and utilization of the major components of urine, mainly nitrogen, in algae reactors in our model BLSS and, at the same time, facilitated the recovery of water excreted in urine.

In conclusion, it should be noted that, in the relatively well-developed BLSS, organic wastes may also be utilized by elements of the heterotrophic component—traditional or nontraditional producers of animal biomass or specially introduced saprophages. For example, we studied the physiological and ecological characteristics of the ordinary housefly, which, in the larval stage, consumes solid human wastes and can serve as food for domestic birds,[42] whereas the residual product is an effective, biologically active supplement to the substrate for growing higher plants.

In general terms, this is the structural and functional organization of the BLSS, in which each of the functional components (subsystems) is responsible for one portion of the overall cycle (Fig. 1) that unites these components into a single, functionally integrated, biological system. Using these components, which are necessary to any ecosystem, one can construct different BLSS variants that resemble natural ecosystems, with their characteristic stability based on the internal interactions of parts to a greater or lesser extent. We merely note that each functional component of the BLSS reveals its true functional parameters (the productivity, quantity, and quality of biomass produced; the relationship to its environment; and others) only when it operates within a specific BLSS model that includes humans and other components. Research with such models has shown that, in general, the characteristics of a potential BLSS component tested in open laboratory facilities do not correspond to those shown during joint functioning with other BLSS components in a closed environment.

There is another aspect of the use of these components of a BLSS. They may act as independent components within a nonbiological system and be used to supplement life support systems based on stored supplies or physical-chemical regeneration. Recently, there has been a trend to use components this way; and this has given rise to the idea of a new class of life support system—mixed (hybrid) systems incorporating processes particular to both physical-chemical and biological regeneration, which had previously been considered alternatives. The category of hybrid systems also covers a variety of systems transitional between the two pure types as the functions of the biological components increase. Of course, inclusion of isolated biological components (e.g., a facility for growing edible plants or maintaining animals) in a physical-chemical system does not make this system biological, although it suggests the potential for development into a biological system in the future.

III. Hybrid Biological-Physical-Chemical Life Support Systems (Controlled Ecological Life Support Systems)

NASA, with the participation of scientists from Japan, Canada, and a number of European nations, is developing the best known of these projects, the CELSS program, for Space Station, lunar bases, etc. [Note: As used in this section, the term "ecological" in CELSS refers to the human living environment and does not correspond to the concept of a biological (ecological) life support system, as the term is used elsewhere in the current chapter.]

The CELSS concept is based upon the integration of biological, physical, and chemical processes to develop safe and reliable life support systems that will produce palatable food, potable water, and a breathable atmosphere by recycling metabolic and other wastes. The central feature of a CELSS is the use of green plant photosynthesis to produce food, with the resulting production of oxygen and potable water and removal of carbon dioxide. For additional information, see Refs. 43-45.

A CELSS is an integrated set of biological and nonbiological subsystems that function through processes of regeneration and recycling to sustain human life. The essence of the system is the production of biomass that can be converted into food, while generating minimal inedible residue, which must be further processed as waste matter before it can be

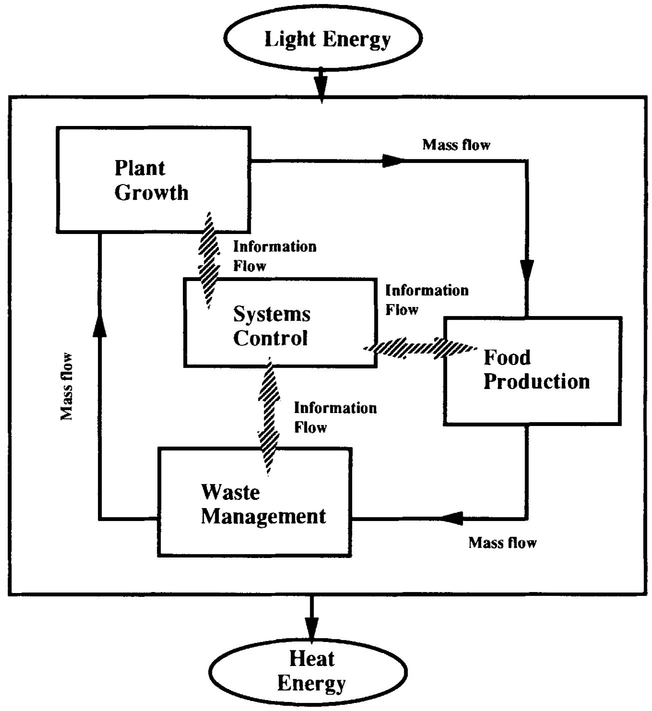


Fig. 2 Prototype ecosynthetic life support system showing inputs, outputs, and internal linkages between functional components.

recycled. The major functions of the CELSS subsystems are biomass production, food processing, waste processing, and system monitoring and control. Because these subsystems are interactive and interdependent, a total systems approach is critical. Figure 2 shows the proposed structure of linkages between the plant growth subsystem and others. Because volume, weight, and energy are all at a premium in space, a particular crop's desirability is judged partly on the basis of how much edible food it can continually produce in a given volume and the amount of light, nutrients, and growing time it requires. Thus, much of the early research in this area focused on maximizing the productivity of specific crop plants. The results of NASA's studies of wheat are summarized in Section II.A.1.

A. Food Production Subsystem

A necessary function of any life support system is to supply appetizing and nutritionally adequate diets for the crew. In theory, these diets could consist solely of vegetables or of vegetables combined with animal proteins or nontraditional foods (i.e., carbohydrates derived from cellulose degradation). Plant combinations that provide suitable diets are selected on the basis of harvestability, palatability, processing requirements, nutritional content, growth habitat, and power requirements. Mathematical models incorporating these characteristics are being developed to determine optimal plant combinations. Preliminary calculations indicate that 99 percent of the crew's nutritional requirements could be met with only three or four plant types (for example, legumes, grains, and vegetables).

Although most crops to date have been chosen for their high ratio of edible food to total biomass, researchers continue to explore methods of converting inedible biomass to food. Candidate techniques include microbial, chemical, and enzymatic processes. Microbial food sources, particularly yeast and algae, are candidates for nutritional supplements.

Biomass generated by crop plants will require processing to make it suitable for human consumption. Studies are now underway to define systems that will harvest, preprocess, store, and convert plant biomass into edible forms. Related research focuses on general food processing methods and examines microbial, chemical, and enzymatic systems as candidate techniques for food conversion. Techniques have been developed to recover a pure protein concentrate from algae grown under controlled conditions.

B. Waste Management Subsystem

In a completely closed environment where all foods are grown onboard and all wastes are recycled into foods, the material balance for the necessary chemical elements can be closed in a manner analogous to that which occurs on Earth. For additional information in this area, see Refs. 41 and 46-48.

Carbon, oxygen, and hydrogen, the three major elements involved in human and animal metabolism appear in the form of carbon dioxide, water, and partially oxidized organics in feces, urine, and exhaled breath. If only carbohydrates, the molecules of which comprise carbon and water, are subject to oxidation in the human body, then the net effect of human and animal metabolism and subsequent oxidation is the exact inverse of photosynthesis.

Water that is not utilized in metabolic processes is essentially used as a carrier fluid within the living components and is used externally in waste processing subsystems. Thus, physical separation processes should be sufficient to recycle water in wastes for use as drinking water, sanitary water, and wash water.

The nutrient solutions used for growing plants in controlled growth chambers invariably contain 12 to 16 elements that are present as inorganic salts and the organic chelating agents needed to maintain some of the ions in solution. These elements (which act as plant nutrients) appear in the waste streams in the forms of spent nutrient solutions, inedible vegetation, uneaten foods, food processing wastes, human and animal metabolic wastes, and animal processing wastes. One major function of the waste processing system is to recover the plant nutrient elements from the various waste streams and convert them back into forms that plants can reassimilate into the food chain.

The functions of the CELSS waste processing subsystems are to convert all wastes into the inputs required to sustain life and to remove contaminants that may be harmful or impair functioning of the living components of the habitat. The major inputs required to sustain human life are food, oxygen, drinking water, sanitary water, and wash water. The major waste outputs include a) solids (human and animal feces, inedible vegetation, uneaten foods, food processing wastes, and animal processing wastes); b) liquids (human and animal urine, spent nutrient solutions, and spent wash water); and c) gases (oxygen from plants, carbon dioxide from humans and animals, water vapor, and off-gases).

The following subsystem technologies have been researched and developed to varying degrees:

- Oxidation of organics by incineration
- Wet oxidation of organics
- Biological oxidation of organics
- Integrated algal bacterial systems
- Higher plants grown on urine
- Wash water recycle
- Atmosphere decontamination
- Carbon dioxide and oxygen extraction
- Recovery of plant nutrients and trace metals from solid and liquid waste streams

None of these technologies has been studied previously in terms of adaptability to the specific requirements of the CELSS concept. For example, the three alternative oxidation processes (incineration, wet oxidation, and biological oxidation) are well-developed technologies for terrestrial applications; the first two have also been researched by NASA for limited space applications. However, even for what are normally considered "well-developed technologies" on Earth, significant research and development are required to determine how readily they can be adapted to a CELSS waste treatment process.

Precise measurement and characterization of system inputs, outputs, and operating parameters are required to obtain detailed mass and energy balances. These data are needed to establish the engineering interfaces and the design of accompanying subsystems. For example, the concentrations and types of organics in the off-gas, which are functions of operating temperature and mode of operation, will define the need for subsequent catalytic oxidation of the off-gas. The degree to which nitrogen is formed during the oxidation of organic nitrogen will determine the need for a separate nitrogen-fixing subsystem in the overall processing scheme. The forms and concentrations of metals in the ash, which may be a function of oxidation temperature, will have ramifications for the methods used to solubilize and separate the ash components in the preparation of plant nutrients.

C. Systems Control

The success of a life support system depends upon the integration of the biological and nonbiological processes and subsystems into a reliable and predictable system. To accomplish this goal, system monitoring and control strategies and technologies need to be developed and tested. Initial research has focused on conducting a number of theoretical studies based upon the application of engineering control theory.

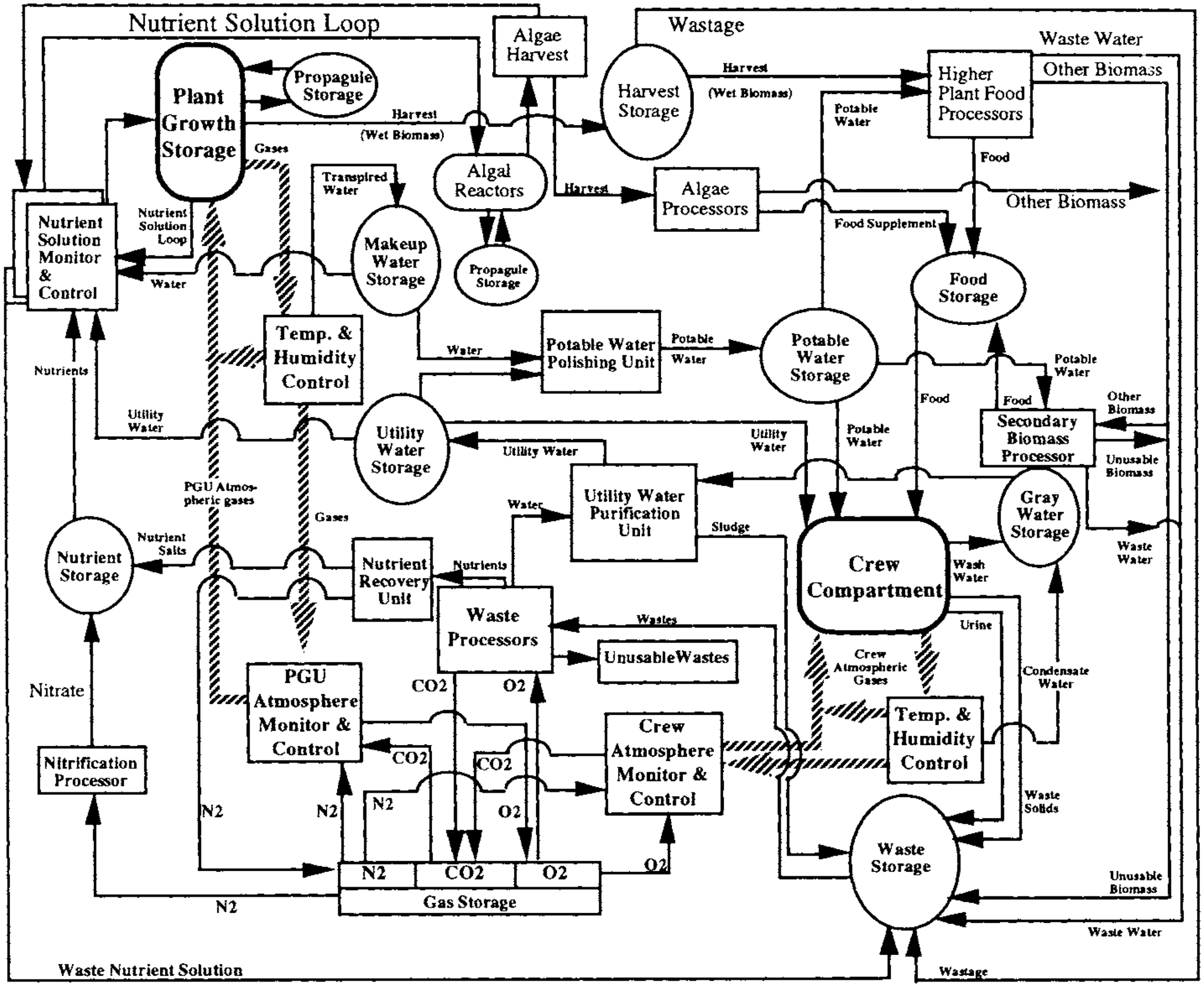


Fig. 3 CELSS initial reference configuration.

The results of the initial research in this area have focused on the production of mathematical models that could be subjected to various system control approaches. A critical conclusion from these studies is the demonstration that certain ecosynthetic life support systems may well be susceptible to long-term failure modes and that the design of control systems to deal with such failures will be crucial to mission success.

D. Initial Reference Configuration for the Controlled Ecological Life Support System

Figure 3 shows a prototype CELSS reference configuration. This configuration will be used for future CELSS investigative efforts and will highlight those subsystems that require intensive planning and research, particularly for a ground-based human-rated CELSS test bed. The evaluation criteria to be applied to a successful ground-based test will address not only the maintenance of air, water, and food production within acceptable limits but also the practicality of achieving the specified results and the resilience of the system across a wide variety of failure modes. Therefore, the test system will incorporate, to the maximum possible extent, the modularity and flexibility desired for an operational system. The crew interfaces will be developed to the extent that only minor enhancements will be needed to adapt the CELSS for operational use. Amendments will be made to the reference configuration as necessary, but its general structure will remain similar to that described herein.

The functions of the CELSS include atmospheric pressure and composition control, temperature and humidity control, atmosphere revitalization, water management, food production, and waste management. Requirements for the proof-of-concept test involve maintaining those functions for a specified time at predetermined performance levels.

The overall system design emphasizes modularity in the

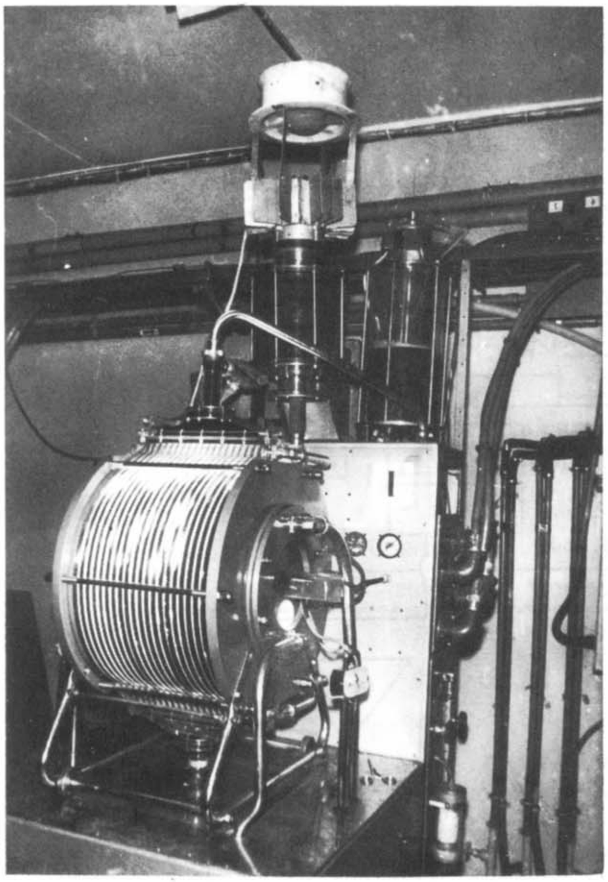


Fig. 4 Photosynthetic reactor (gas exchanger).

processors (plants, waste, and crew) that interact through connections to material reservoirs (storage tanks and cabin atmospheres). The system will also allow operation in a number of alternate modes to allow maximum flexibility in coping with single-point failures. System-level control of the CELSS will be enabled by reference to a computer-based emulation model, which will have a simplified crew interface and mode selection.

In conclusion, it should be said that hybrid biological-physical-chemical systems are sure to be the first actual instances of the partial use of the biological method of regeneration in a life support system.

IV. Experimental Biological Life Support System Models

After the first attempts in the 1960s in the U.S.S.R. to create a BLSS based on photosynthesis of one-celled algae (see Sections II.A.1 and II.A.2), a long period of research was required before these endeavors could resume at a new level of algae productivity, using a continuous noncirculating flow method of cultivation. Even more important, the new systems were based on a new level of understanding of the problem of the BLSS itself, not as an applied technological task but as an independent ecological problem—the creation of artificial closed ecological systems, of which the BLSS is an example.

At present in Russia, various BLSS models have been developed and studied, from the simplest, based on one-celled algae, up to models including (or exclusively based on) higher plants and components of a system for mineralization and utilization of organic wastes. The best known and most highly publicized data are those generated by "man-higher plants" models studied in the Institute of Biophysics of the Siberian Division of the Russian Academy of Sciences (Krasnoyarsk) using the Bios-3 facility.[49,89–91]

In this chapter, however, we will concentrate on less widely known data concerning the environment generated in the BLSS models, human physiological reactions to this environment, the closure of these models with respect to mass exchange, their stability, and other aspects of their correspondence (or lack thereof) to the major properties of natural ecosystems. These data were obtained in the Institute of Biomedical Problems of the U.S.S.R. (currently Russian) Ministry of Health (Moscow).[50,51]

A. Models of the Biological Life Support System Based on One-Celled Algae

The major functional component of this model is a nonsterile, noncirculating culture of the one-celled algae, *Chlorella vulgaris*, in a photosynthetic reactor (Fig. 4). The reactor is cylindrical in shape with xenon luminescent lamps of 6 kW along its long axis. The light falls directly on the base of wedge-shaped light guides made of acrylic plastic and is directed into the center of the algae suspension, which is located between the light guides and the outer wall of the cylinder. The volume of the suspension in the gas exchanger is approximately 15 liters, with a working density of 10–12 grams of dry substance per liter. The working density is supported at the appropriate level through automatic removal of a portion of the suspension at a signal from a photoelectric density sensor, with simultaneous addition of a nutrient medium balanced for mineral elements, along with condensate of water vapor from the inhabited module. Air is blown through the reactor at a rate of approximately 200 L/min. Human gas exchange is supported by three, or (less frequently) two, such reactors. After passing through the reactors, the air enters a pressurized cabin inhabited by humans, which has a free volume of 5 m^3. A flow chart of the structure of this model is presented in Fig. 5.

Aside from humans and *Chlorella*, the model contains units for biological mineralization and dehydration of urine and for drying solid human wastes and unusable *Chlorella* biomass for return of free water to the overall cycle. These units are used, also, when a higher plant component is added to this model.

The component for biological mineralization of urine is designed for regeneration and repeated use of the water and nitrogen excreted by humans in urine, and also of the carbon dioxide that forms when urea decomposes. The process in-

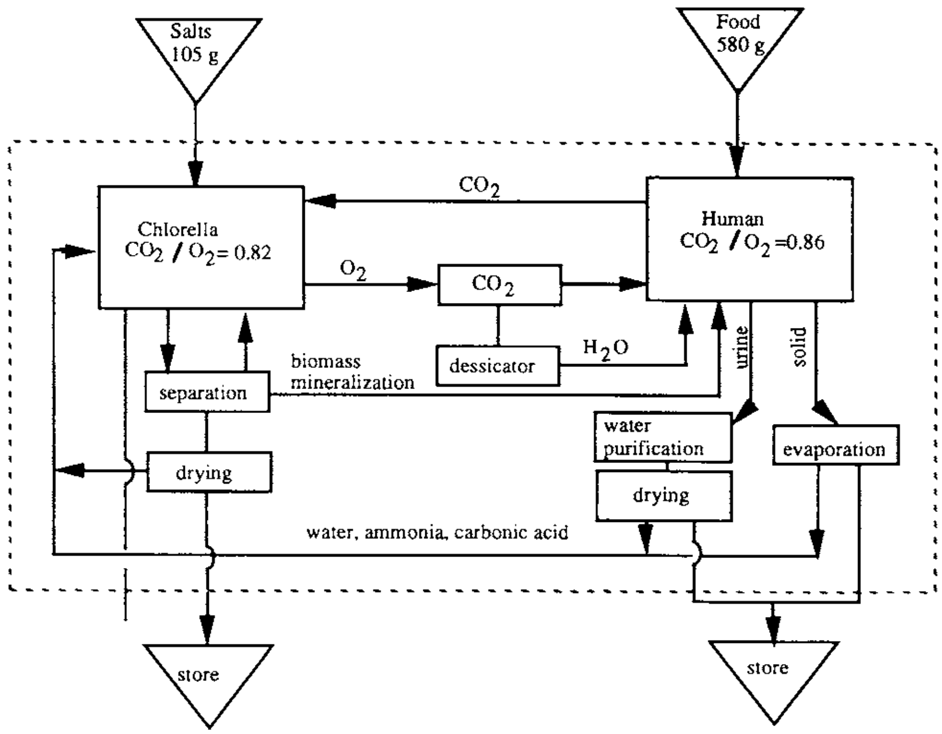


Fig. 5 Functional structure of a "human-*Chlorella*-mineralization" model.

volves preliminary processing of urine in a special fermenter by urobacteria, followed by distillation of water and ammonia in an evaporator. Water vapor containing ammonia and other components is either fed into the algae reactor directly or is passed through a cell containing nitric acid, where the ammonia is bound into ammonium nitrate and is fed into the algae suspension as a component of the corrective solution to compensate for loss of nitrogen from the medium. Dehydration of unusable biomass (after centrifugation) and feces occurs at a temperature of 70–80° in an air stream and then enters the algae reactor without undergoing any cleaning.

1. Material Balance in the Biological Life Support System Model

The human and algae food chain in the models under discussion have remained almost completely open. System inputs from without included mineral salts for the algae and food for the humans with a total energy value of 2450–2700 kcal/day, to which were added 50 grams of dry biomass from harvested *Chlorella*. The nitrogen fed to the algae was partially provided by nitrogen in urine, approximately 10 percent of which was returned to the human diet in the biomass of *Chlorella*. The unusable algae biomass and solid human waste exited the system (see the flow chart in Fig. 5) after dehydration.

The model provided a complete water regeneration cycle. The water generated by the cycle was used as drinking water, in food preparation, and for hygienic purposes by the humans and was consumed by the algae in the process of photosynthesis. Human transpirational water and free water from urine, feces, and algae biomass were regenerated and recycled. All the water entered the photosynthetic reactor in the form of gas and was output as condensate in an amount corresponding to the amount consumed. The condensate obtained was subjected to further cleaning through sorption, disinfection, and saturation with mineral salts, using a method developed at the Institute of Biomedical Problems and employed on space station Mir.[52] The water obtained met hygienic standards for potable water.

However, a fully closed water cycle was not possible in this system because water entered from without in the food ration and, in combination with organic substances, left the system in the form of dried fecal residue and algae biomass. These external "inputs" and "outputs" essentially were balanced, allowing the system to function without addition of water to the initial supply. The loss from the system because of bound water in food and discarded wastes amounted to approximately 9 percent of its daily turnover. The 91 percent closure of the water cycle thus attained is probably the maximum possible level for a system with external supplies of food and disposal of dry residue of organic wastes.[51]

The model achieved complete regeneration of oxygen. The productivity of the photosynthetic reactors was initially made to correspond to the oxygen consumption rate in the system by selecting the level of illumination for the algae culture. This correspondence was stable throughout the experiments (up to 30 days) and did not require corrective adjustment (Fig. 6, curve 1). However, concentrations of carbon dioxide in the system increased continuously (Fig. 6, curve 2) and the ex-

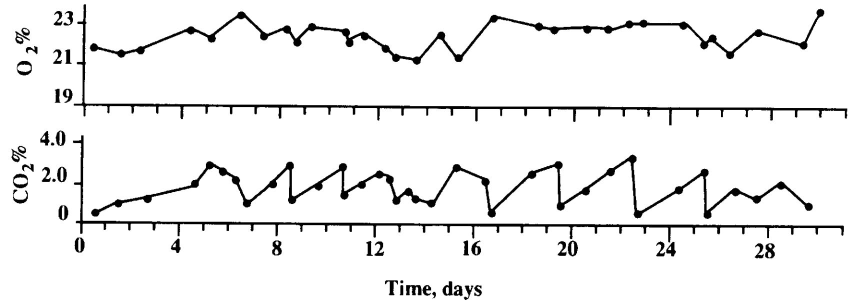


Fig. 6 Dynamics of oxygen and carbon dioxide levels in the atmosphere.

Table 5 Percent of substances regenerated in two BLSS models

Substance	Consumed, grams/day	Man-algae-mineralization model Regenerated		Man-algae-mineralization-higher plants model Regenerated	
		Grams/day	Percent	Grams/day	Percent
Oxygen	755	755	100	755	100
Food	530	50	9	138	26
Water	3400	3400	100	3400	100
Total	4685	4205	90	4293	92

cess had to be absorbed by chemical absorbers approximately once every 2-1/2 days.

This gas exchange imbalance occurs because the assimilation coefficient of algae (amount of absorbed carbon dioxide per unit of emitted oxygen) is determined by the composition of the biomass synthesized by the algae, whereas the inverse ratio of these gases in human respiration (respiratory quotient) is determined by the composition of food assimilated, which differs significantly from the composition of the algae. Evidently, complete gas balance can be attained only in rather complex multispecies systems, in which the entire output of the photoautotrophic component is fully utilized in the trophic chains of the heterotrophic organisms. In the models studied, excess carbon dioxide equaled 5–7 percent of its daily turnover.

Despite the simplicity of the biocenotic structure of the "humans-algae-mineralization" models studied, they are able to regenerate the oxygen and water in amounts that fully meet human needs. However, they can meet the need for food only partially (up to 10 percent of total mass). The total amounts of regenerated substances produced in such a system are presented in Table 5. This system, which produces approximately 90 percent of the quantity of substances consumed, is evidently close to the maximum possible efficiency for systems with analogous structures; i.e., those in which the photosynthetic component is represented by only one species of plant, which makes up only a small proportion of the diet. In models such as this, having incomplete closure with respect to trophic linkages, it is important to keep the substances input to and output from the system in balance. This maintains the material and, thus, the functional equilibrium of the system over time.

Significant characteristics of the models being studied are the small air volume of the system (5 m^3 per person), the low initial supply of oxygen (1 m^3 per person), and the low initial supply of water (52 liters per person), including that used in the algae suspension. These system parameters are of great importance, since they determine the duration of recovery cycles for water and oxygen, the major system components. Because of the system's low volume and the small initial amounts of regenerable substances needed, speed of regeneration is high so that, during a typical experiment (30 days), up to 15 cycles of oxygen and almost 2 cycles of available water are regenerated. Some data suggest that renewal of the supply of oxygen in the Earth's atmosphere requires 2000 years. This comparison demonstrates one property that makes small-scale models with relatively small initial supplies of regenerable substances useful for experimental ecology.

2. Volatile Components of the Atmosphere

Volatile contaminants in the atmosphere are an important factor in the habitability of a BLSS. The atmospheres of autonomously functioning BLSS subsystems (for algae suspension, urine mineralization, and dehydration of solid wastes and algae biomass) have been found to contain dozens of organic compounds, the predominant ones being hydrocarbons (C_1–C_5), aldehydes, ketones (C_3–C_5), carbonic acids, alcohols, and complex esters. Many compounds remain unidentified.

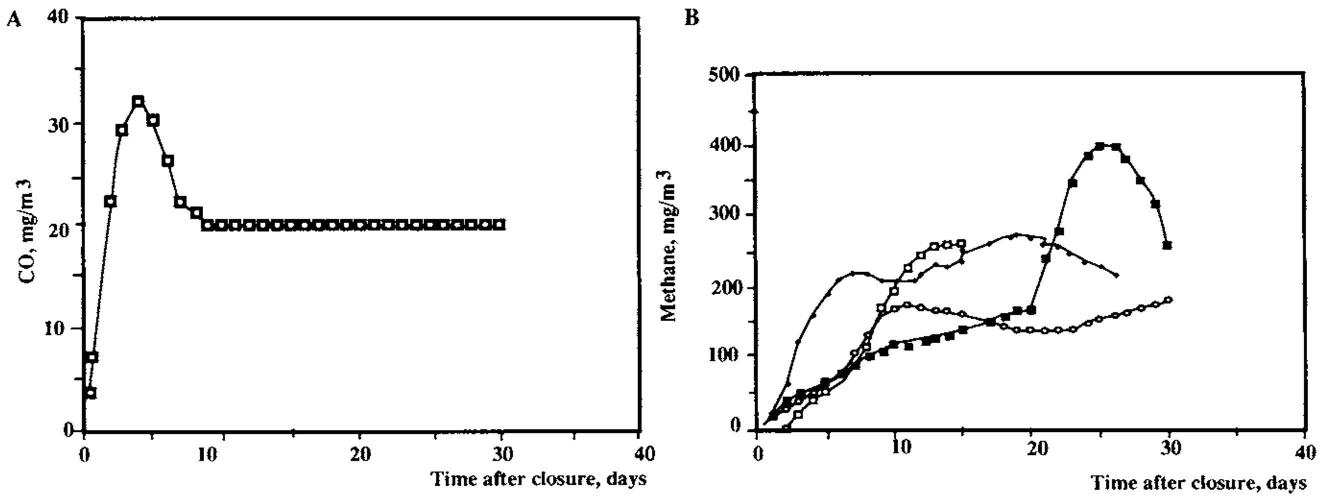


Fig. 7 Dynamics of concentration of carbon monoxide (A) and methane (B) in the atmosphere of the model studied (for methane, each trial is plotted separately).

When individual components are linked to form a single system, the water-soluble contaminants in the atmosphere have been found to consist primarily of aldehydes and ethyl alcohol in concentrations up to 0.5 mg/L. The less soluble components (carbon monoxide and methane) accumulate in the atmosphere, and stabilize at a certain level. The equilibrium concentration for carbon monoxide was approximately 20 mg/m^3 (Fig. 7A), and for methane 150–250 mg/m^3 (Fig. 7B). There are two phases in the pattern of change of these components over time: an accumulation phase and a stationary phase. Time required for carbon monoxide to reach the stationary phase was found to be 4–6 days after closure of the system, with inclusion of humans (Fig. 7A); for methane, time required was 7–10 days (Fig. 7B). Occasional jumps in the levels of certain volatile components were transient and associated with disruption of the thermal regime for drying organic wastes.

The dynamics of concentrations of volatile components in the atmosphere of the BLSS demonstrates that the system must have certain mechanisms for binding these components. Evidently, the photosynthetic reactor, with its algobacterial community, acted as a hydrobiological filter for removing volatile components from the atmosphere. These substances not only dissolved in the liquid medium but also were utilized in the suspension of algae and concomitant microflora and were thereby drawn into the overall cycle.

It must be noted that the general results of the combined gas-forming and gas-absorbing activity of the functional components of the system were studied in the absence of any filtering or absorbing devices. In a number of cases, this caused standards for acceptable concentrations of certain contaminants (e.g., carbon monoxide) to be exceeded temporarily. However, had filters been used, it would not have been possible to identify the system's tendencies and capacities to stabilize volatile components in the regenerated atmosphere.

The capacity of the algae suspension to assimilate volatile atmospheric components was not studied specifically but potentially could be very large. For example, the suspension assimilated the nitrogen in urine after urea decomposed producing ammonia. Thus, the use of one-celled algae in a BLSS revealed the system's unanticipated capacity to stabilize volatile components when the atmosphere was regenerated without special filters.

Investigations of these models revealed an additional unanticipated function, optimization of the composition of charged components of the atmosphere—aero-ions. Throughout all the experiments, light, negatively charged ions with a coefficient of unipolarity of approximately 0.6 and a total concentration of 1.3–1.5 x 10^3 ion/mL were predominant in the system's atmosphere. This type of ionization is characteristic of the atmosphere of coastal regions and open areas covered with vegetation and is not observed in the atmosphere of inhabited enclosures with non-biological LSSs. This is of great significance from the standpoint of the quality and adequacy of the human living environment formed in the BLSS. A detailed analysis of this issue was presented in a work by A.V. Anisimov, a scientist of the Institute of Biomedical Problems.[53]

3. Micro-Organisms in the Biological Life Support System

Still another unanticipated function of a system based on one-celled algae was discovered when microbial composition and dynamics were studied in the atmosphere of these BLSS models.

Microbiological issues are among the most important in space medicine with respect to flights of spacecraft and space stations (see Chapter 4 of this volume). In a BLSS, as a closed ecosystem, a new aspect of space microbiology becomes salient. This is the case because the human indigenous microflora that predominate in spacecraft environments are only a fraction of the total microecosystem of a BLSS. Each BLSS

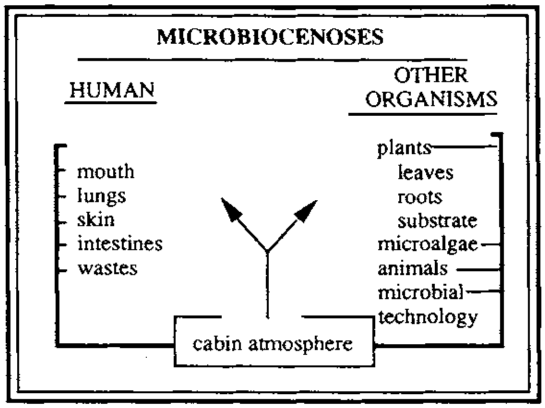
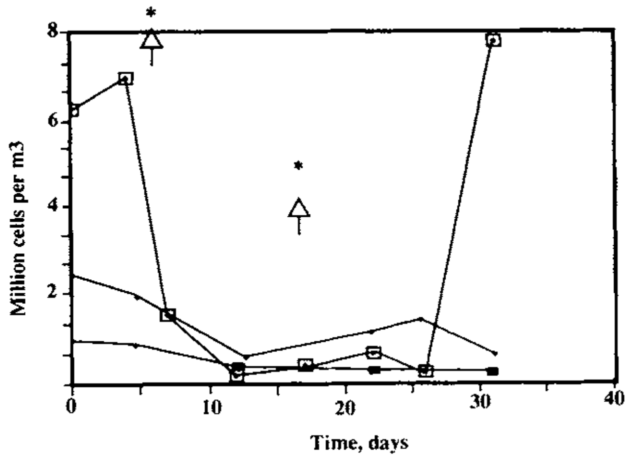


Fig. 8 Structure of a microbial community in a BLSS.



* indicate points at which bacterial count increased due to short periods of depressurization of the system

Fig. 9 Dynamics of total bacterial count in the atmosphere of a BLSS in two experiments (curves 1 and 2) and *Staphylococci* count (curve 3).

component may have concomitant microflora that coexist with one another in complex and unanticipated interrelationships and form a kind of system within the larger BLSS macroecosystem, which itself may be studied from an ecological standpoint.

The literature on BLSSs includes valuable information on the microflora of the individual components of the ecosystem, one-celled algae[54] and higher plants.[55,56] However, with the exception of work by J.I. Gitelzon et al.,[57] these studies remain isolated and have not influenced the study of the microecosystem as an integrated component of the BLSS and an independent ecological factor.

Our own investigations have also concentrated on the microflora of individual biotopes of the BLSS. However, they can provide the foundation for an initial attempt to conceptualize the problem of the overall microbiology of the BLSS. The structure of the microbiocenosis of the BLSS is depicted schematically in Fig. 8. The BLSS microflora represent a system of relatively isolated but ultimately interrelated communities of micro-organisms occupying various ecological niches in human biotopes, other functional components of the ecosystem, and the equipment and interior of the spacecraft. Isolation of individual biotopes is relative and does not prevent cross-exchange among their microcenoses. For example, representatives of intestinal microflora are periodically found among the microflora of the spacecraft interior, the nasopharynges of crewmembers,[58] and the root areas and nutrient media of the higher plants.[59]

The associations among various microbial communities may take the form of a systematic incursion of alien flora, followed by their inevitable elimination in a developing community. But the association may also be more complicated, taking the form of competition or symbiosis and complementary functions in the assimilation of ambient trophic resources, when complex substances must be decomposed through the action of various micro-organisms with different types of metabolism. The latter situation is most likely in organic waste collectors but is possible, also, in biotopes of the interior, which is full of decay-resistant polymer materials with various chemical structures.

The atmosphere plays an important role in the microecosystem of the BLSS. It is a kind of central "communications center," the arena of communications among microbial communities of various biotopes. Thus, atmospheric microflora may carry information about the state of these communities. Moreover, the atmosphere is the source of organic hydrogen for micro-organisms growing on inert substrates having only limited trophic resources or none at all. Here, we are referring to various structural and decorative materials, on which, according to A.N. Viktorov's data,[60] stable fungal communities of micro-organisms are established (see, also, Chapter 4 of this volume). One must assume that atmospheric moisture and the organic components of the atmosphere provide sufficient resources to sustain such communities. The role of these factors as sources of nutrition for atmospheric microflora was first noted by N.G. Kholodnyy.[61]

In the BLSS models we studied, the qualitative and quantitative composition of the system's microbiocenosis was determined by at least three interacting sources of microflora: human indigenous microflora, the microcenosis of the nonsterile cultures of algae, and microflora of the urine collector and mineralization fermenter. Typical overall population dynamics for bacteria in the atmosphere of the inhabited system are presented in Fig. 9, which depicts data from two experiments. This figure shows that the initial number of microflora decreased after closure of the system and stabilized at a rather low level—approximately 10^3 cells in 1 m^3 of air. This level is one to two orders of magnitude below that typically observed in ground experiments with non-biological LSSs or on manned flights on Salyut space stations.[58] The two points in the figure where one can see sharp increases in the number of microflora were associated with periods of short-term depressurization of the inhabited cabin (indicated by arrows) in one of the experiments. In the other experiment, a similar increase occurred at the end of the experi-

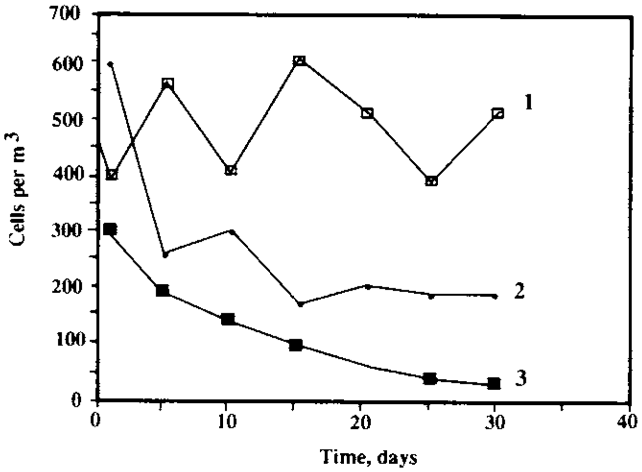


Fig. 10 Dynamics of the number of hemolytic *Staphylococci* in the atmosphere of an office (1), inhabited cabin (2), and greenhouse (3) modules of a BLSS.

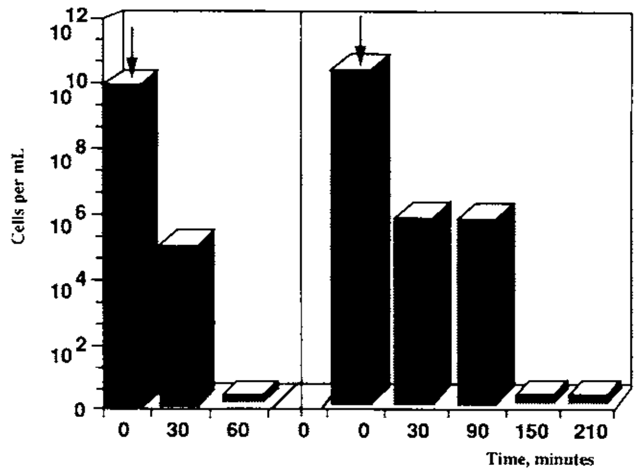


Fig. 11 Elimination of pathogenic *Staphylococci* in an algae suspension (arrows indicate the point at which *Staphylococci* were introduced into the suspension).

ment, when an air sample was taken several minutes after the inhabited cabin was opened. This short period was sufficient to allow incursion of microflora from the surrounding environment. It is important that in the BLSS, after temporary depressurization of the system, the bacteria immediately return to their initial level, demonstrating the existence of internal mechanisms for stabilizing the bacterial community in the face of external disturbances. The progressive divergence in the levels of bacterial contamination of pressurized BLSS modules (e.g., inhabited greenhouse) and the atmosphere of an office environment are shown in Fig. 10.

In models of the BLSS based on one-celled algae, the microbiocenosis that forms spontaneously in the algae culture plays a significant role in generating the atmosphere. The limited levels of volatile organic components in the atmosphere, as discussed above, are largely due to the microflora associated with the algae. The dynamics of changes in the levels of methane in the atmosphere presented in Fig. 7B are of special interest here. The absorption of methane and its stabilization in the atmosphere, which occur later than the analogous processes for carbon monoxide, indicate that the responsible process develops after the closed system starts to function, attesting to the capacity of the established bacteriocenosis to undergo adaptive changes in structure when new trophic resources appear. It is evident that a new ecological niche begins to form, consisting of methane-oxidizing bacteria and members of the extensive *Pseudomonas* group, typically the predominant representative of microflora in an algae reactor. This could be the result either of selection and increase in forms already capable of methane oxidation or of the appearance of active enzymatic systems in previously inactive forms of bacteria. This empirical demonstration of self-adjustment (self-modification) exemplies one of the fundamental properties of ecological systems, which is realizable even in a biocenotic structure as simple as the BLSS models studied.

With respect to species composition, the predominant microflora in the BLSS are forms that are functionally (trophically) associated with the skin and mucous membranes of the human upper respiratory tract (as a natural ecological niche). The dynamics of levels of the major groups of microorganisms are analogous to the dynamics of total levels but are less pronounced. An important feature of the behavior of atmospheric microflora in the BLSS is the decrease in the proportion of pathogenic forms of bacteria, particularly hemolytically active forms of *Staphylococci*. The practical importance of this phenomenon for general habitability considerations required that it be experimentally verified.

To accomplish this, at the end of one of the 1-month experiments on BLSS models, a culture of algae in the photosynthetic reactor was inoculated with measured amounts of labeled (phagotyped) strains of hemolytic *Staphylococci*, after which their levels in the suspension and atmosphere were measured (work performed by G. O. Pozharskiy). It was established that, as early as 2–4 h after inoculation (depending on the amount of bacteria added), no bacteria were evident in either the algae suspension or the atmosphere (Fig. 11). This effect is consistent with the general fate of the majority of species artificially introduced into ecosystems, which fail to find suitable ecological niches or else encounter unforeseen competition, ultimately leading to their displacement by local forms. In this case, the phenomenon occurred relatively rapidly—within a single microbial generation. This provided a very clear example of the ecological stability of the leading microbiocenosis of algae in the BLSS and its important role in the formation of a microbiologically wholesome atmosphere for human habitation.

It is obvious that the mechanism underlying the stabilization of the number and species composition of microflora (through ecological self-regulation of the microbiocenosis) that is characteristic of this model would not be possible in a system where human microflora failed to encounter ecological resistance from other microcenoses and, thus, were able to grow progressively without experiencing pressure from the biological environment. This is precisely what occurs when humans are isolated in systems with non-biological LSSs. Under these conditions, the prospects for the success of a long-term, possibly multiyear, exposure of humans to their own microflora seem ecologically dubious, given the high adaptability of micro-organisms and the lesser flexibility of the human immune system. For this reason, special sanitary and microbiological measures would inevitably be required (see Chapter 4 of this volume).

4. Biological Life Support System Reliability Issues

Like natural ecosystems, the BLSS can survive independently in a state of long-term dynamic equilibrium. This feature resembles the concept of system reliability. In the literature, we often encounter the statement that biological systems are relatively unreliable, especially when compared to physical-chemical systems. One must bear in mind that BLSS reliability has two aspects: the technological and the biological. The technological aspect relates to the reliability of the numerous units and assemblies of the BLSS and is subject to analyses based on existing theory and methods for evaluating the reliability of technological systems.

At present, the theory and methods needed for evaluating the reliability of biological systems do not exist. However, a good candidate for a reliability criterion is long-term, stable survival of living systems at all levels of biological organization—from individual organisms with their characteristic lifespans, which are a species attribute, to populations, biocenoses, and ecosystems with long-term stability of survival on a historical scale—encompassing an enormous number of generations of the leading species in natural ecosystems. Yu.M. Svirezhev and D.O. Logofet performed a mathematical analysis of the stability of such systems.[62]

The stability of living systems is based on such properties as multiple levels of redundancy, self-propagation, self-repair after damage, self-regulation with respect to changes in external conditions, and adaptivity of structure and function. For this reason, the concept of system reliability developed in engineering is not really appropriate to living systems, especially since the engineers define reliability in multiple ways. For example, distinctions are drawn between Lyapunov reliability and Lagrange reliability.[62] Certain qualitative ideas concerning reliability in a BLSS are presented in a work by the present authors.[63]

With respect to the BLSS, it seems more appropriate to use the concept of stability, which we define as the capacity of a biological system at any level for long-term survival, under a certain range of conditions, while maintaining major functional characteristics within a normal range of fluctuations. From this point of view, we will consider the BLSS models studied.

One of the major results of the study of "man-algae-micro-organisms" models obtained in five experiments lasting 29–31 days was their capacity for long-term stable functioning with the use of the technology and methods of algae cultivation described above, along with their low need for external regulation. Throughout the 1-month periods during which the models functioned, aside from the already noted imbalance of gas exchange (which is inevitable for such systems), no other signs of instability were observed that suggested time limits for their existence. The duration of the experiments was limited to a month only because of the unacceptability of confining humans in a space of 5 m^3 for an indefinite period.

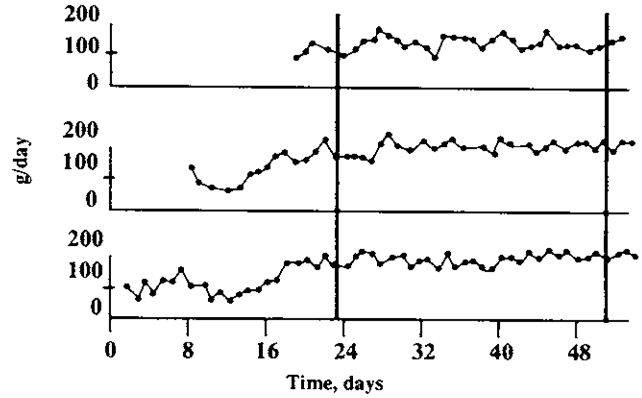


Fig. 12 Productivity of algae in three photosynthetic reactors operating in parallel (vertical lines delimit period in which the reactors were operating as a BLSS component).

All the major functional characteristics of the models stabilized immediately or after a transitional process varying in duration, after which no further major changes were noted. The duration and nature of the transitional processes during the initial period of BLSS functioning must be considered when life support systems are actually used.

The 15 complete oxygen regeneration cycles occurring over a period of a month provide reliable evidence for the stability of the processes in these models, since a system's stability is more appropriately measured in terms of number of cycles of substance regeneration occurring in it (the major result of the system's operation), rather than the duration of the test according to the calendar. After all, these 15 cycles of oxygen regeneration in a system 10 times the size (50 m^3), would take 10 times as long (300 days). This example demonstrates the fundamental principle of functional similarity of regenerative systems, which enables comparative evaluation of various BLSS models with different biocenotic structures and provides a method for accelerated testing of such systems. The issue of similarity of BLSSs is discussed in more detail in Ref. 18.

The stability of the functional characteristics of the models studied is primarily a result of the stability of the characteristics of the algae cultures performing the major functions in the systems. Among these characteristics are productivity (Fig. 12); composition of biomass (Fig. 13); and age structure of the population (Fig. 14), which remains stable for doz-

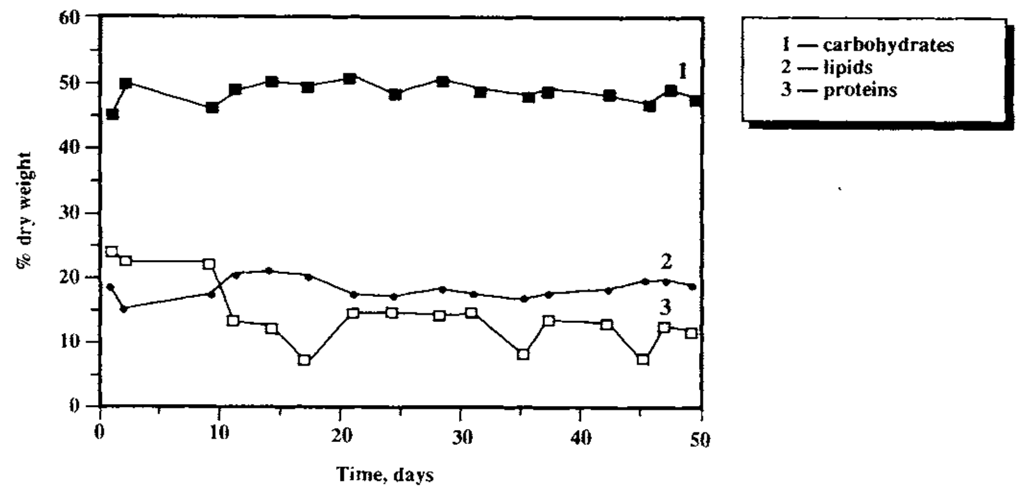


Fig. 13 Composition of *Chlorella* biomass in percent of dry weight during continuous independent cultivation and as a component of a BLSS model (delimited with vertical lines).

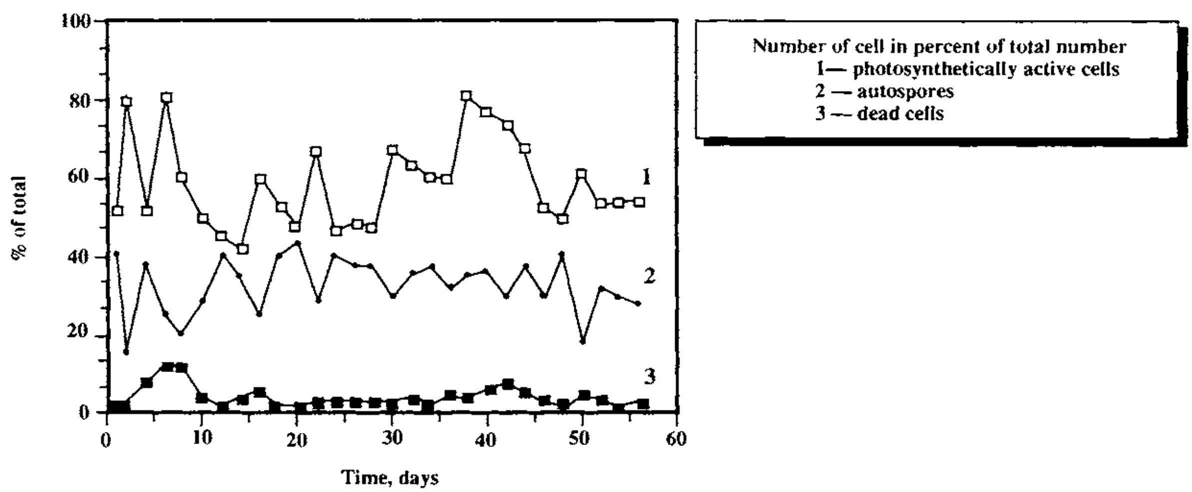


Fig. 14 Age structure of the population of *Chlorella* during continuous cultivation.

ens of cell generations. Except for normal fluctuations around the mean, these parameters undergo no changes. When accidental deviations from the optimal cultivation conditions occurred during the experiments (technical aspect of reliability), the cultures utilized self-repair mechanisms. Although the age group of cells most sensitive to disruption of ambient conditions (e.g., overheating) died, after conditions returned to normal, the culture recovered through the survival of the age group most tolerant of this factor. This is one of the intrapopulation mechanisms for maintaining stability.

The literature frequently discusses the potential genetic instability of systems based on organisms with short developmental cycles, in which a large number of generations must function. With respect to the BLSS, this issue is discussed in the work of J. Cook.[64] It is important to note that the use of the identical strain of *Chlorella* for a period of 25 years in our laboratory unimpeachably demonstrates the genetic stability of BLSSs based on one-celled algae.

The different manifestations of stability of the BLSS model discussed immediately above are inherent in various structural levels of the system. For this reason, it is natural to base analyses of stability of biological systems on their hierarchical multilevel structure. One can then identify the role of various mechanisms for supporting stable system functioning. These mechanisms operate at various levels of biological organization: the ontogenetic ("organism"), population, biocenotic, and ecosystem levels. This approach to ecosystem stability is clearly the most natural and, thus, can facilitate future systematic study of the stability of BLSSs varying in biocenotic structure.[63]

The ontogenetic level of stability is determined by an organism's inherited traits and realized through the mechanisms of homeostatic, adaptive, and defensive reactions. These may be readily modified or may be relatively stable (adaptive modifications or adaptations). The adaptation of enzyme systems to changes in the trophic environment characteristic of micro-organisms is evidently of the latter kind.

At the population level, there are other mechanisms for supporting stability. It is well known that resistance to changes in environmental conditions varies in individuals differing in age. Since the population consists of individuals at various stages of ontogenesis, the probability of this population maintaining a steady state under altered conditions is greater than it would be in a culture of individuals all of the same age. Figure 14 shows the age structure of populations of *Chlorella* under continuous cultivation.

At the level of biocenoses and ecosystems, there are still other mechanisms for supporting stability. An important factor here is species diversity. In ecology it is virtually universally accepted that species diversity is directly tied to community stability. This would truly be the case if differences among closely related species were not only morphological but also functional; i.e., if they played different roles in the overall substance cycle. Evidently, the situation here is more complex. Metabolic diversity of the functions of organisms and diversity of complementary ecological niches, and not the number of diverse units (species) in the system, are the important factors for stability of biological systems. In this case, functional diversity can be interpreted in terms of degree of closure of the cycle and, thus, degree of autonomy and stability of a given ecosystem.

Species diversity of communities (to the extent to which functional differences are involved) creates the conditions for development of different types of symbiotic relationships, increasing the stability of the system. This is, for example, the situation in a nonsterile algae culture, where concomitant microflora solve the problem of disposing of the metabolic products of algae and, most likely, release vitamins and other biological substances needed by the algae into the common medium. This, of course, makes such a culture more stable than a sterile culture.

Thus, in a complex system, each individual organism, which has its own mechanisms to support stability, is also protected by the defense mechanisms characteristic of the higher levels of biological organization—populations, biocenoses, and ecosystems—whereas the stability of higher levels is based on the mechanisms supporting the stability of each subordinate level.

B. Biological Life Support System Models Including Higher Plants

Models of BLSS including higher plants have been studied in the Institute of Biophysics of the Siberian Division of the U.S.S.R. (now Russian) Academy of Sciences (Krasnoyarsk) and the Institute of Biomedical Problems of the U.S.S.R. (now Russian) Ministry of Health (Moscow). Materials relating to the first group of such models have been published extensively[49] and are cited in the American literature.[89–91] We will not repeat this information but will present certain other data related to a less publicized model studied in the Institute for Biomedical Problems. This model included all components of the aforementioned "man-algae-micro-organisms" model, including units for dehydration of organic wastes and mineralization and evaporation of urine. The higher plant subsystem was enclosed in a pressurized environment that included a greenhouse and hydroponic units with a two-tier 15-m^3 growing area (Fig. 15). The greenhouse shared an air supply with a 27-m^3 inhabited module and a 36.5-m^3 air conditioning (dehumidifying and warming) system. The total air volume of the pressurized area was 95 m^3. Wheat occupied 11.25 m^3 of the growing area of the greenhouse, with the balance devoted to vegetables. The plants were illuminated around the clock with 6-kW xenon lamps equipped with water filters. The vegetable crop received 60–80 W/m^3 PAR and the wheat crop received 125–185 W/m^3 PAR of illumination. The plants were cultivated without a substrate with periodic feeding of nutrient solution in the area of their roots. The solution was corrected twice a week, and any losses were countered using condensate collected in the air conditioning system. The majority of the condensate came from the transpirational water of the plants. More detailed information about this model is presented in a work by I.Ye. Ivanova et al.[34]

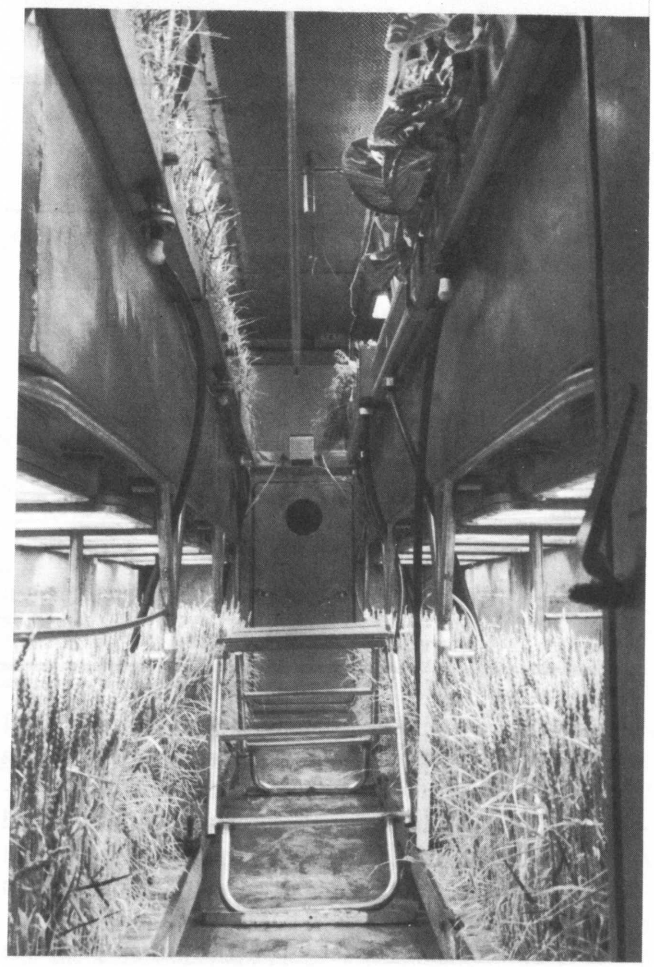


Fig. 15 Interior view of two-tier BLSS greenhouse. In the background is the pressurized hatch into the inhabited module.

The design of the experiment included preliminary opera-

Table 6 Productivity of plants (M±m) [From Ivanova et al.[34]]

Culture	Condition	Increase in dry biomass, $g/m^2/day$ Total	Edible
Wheat	Control	25.8 ± 2.4	5.3 ± 0.7
	Experimental	32.8 ± 1.9	4.7 ± 1.3
Peas	Control	12.8 ± 1.9	3.5 ± 0.9
	Experimental	12.9 ± 3.8	2.3 ± 1.2
Beets	Control	8.4 ± 1.1	3.4 ± 0.8
	Experimental	5.0 ± 3.1	2.3 ± 1.5
Carrots	Control	11.0 ± 4.2	6.0 ± 3.9
	Experimental	9.7 ± 4.2	6.3 ± 3.1
Cabbage	Control	16.0 ± 4.3	14.4 ± 4.2
	Experimental	14.2 ± 4.4	12.9 ± 4.2

tion of the greenhouse in a stationary conveyor mode until the first crops were harvested (control period), after which a single human subject was introduced into the inhabited module. After 15 days, the air supply for this system was joined with that of a "man-*Chlorella*-micro-organisms" system that was already in operation so that they formed a single system including two humans, which then operated for 45 days.

The results obtained on the productivity of the plants are presented in Table 6.

The harvest index of all the plants, except carrots, was lower in the experimental period than in the control period. Here, it should be mentioned that the productivity of plants under greenhouse conditions, even in the absence of a pressurized environment, is significantly below that for open plant growth devices and phytotrons. This phenomenon, observed consistently throughout many years of work, has yet to be explained. An analogous phenomenon was noted by G.M. Lisovskiy.[33]

It is noteworthy that the vegetable culture yields did not decrease during the last period of the experiment, when they were subject to the greatest stress, because the atmosphere was shared with two human subjects; *Chlorella;* and all the other subsystems, including urine evaporation and waste dehydration.

Analysis of wheat yield revealed a pattern of results that was not completely clear. The total yield with respect to biomass during the experimental period increased compared to the period of autonomous growth; however, the grain yield fluctuated sharply, and periods of normal or greater yields compared to control were interrupted by periods of sharp decline or virtual absence of yield (the ears were barren of grain, Fig. 16). There were 4 such periods in the 10 wheat growth cycles occurring during the experimental period. According to Lisovskiy,[33] a similar phenomenon occurred in a pressurized closed system including humans in the Bios-3 facility.

One thing, however, is clear: The reason for the barrenness of the ears in these experiments is not associated with the period of operation of the greenhouse as part of the complete BLSS. The lack of grain is the final result of embryonal damage to the development of the reproductive organs, which are established in the early stages of ontogenesis, 35–40 days before a grain harvest is obtained. Thus, the period responsible for the lack of grain occurred, for the first three of four cases, during the control period; and the cause of the harvest failure could not have been associated with one of the other components of the model, which were only introduced later. Overall, the higher plant component synthesized 432 grams of dry biomass daily, including 86 grams of edible substance (20 percent), of which 54 grams were wheat and 32 grams were vegetables.

In this experiment, in order to maximize use of plant biomass, nontraditional portions of the plant were included in the diet, including the tops of carrots, beets, peas, and cabbage. The vegetable mass was chopped mechanically and juice was extracted, the amount of which reached 60 percent of the initial moisture level of the wastes. Pulsed electrical blending of the initial mass increased the yield of juice to 80–85 percent of the free water contained. The dry substance of the juice comprised 40 percent carbohydrate and 18–30 percent protein.[65]

The actual daily diet of the subjects included a mean of 137 grams of dry biomass substance produced in the system, including 50 grams of *Chlorella*, with a total energy value of 454 kcal/day. This comprised 26 percent of the diet by weight and 19 percent of the calories. The protein produced in the system comprised 33 percent of all dietary protein (37 grams), of which 20 grams were *Chlorella* biomass. As a result, the level of regeneration of substances was somewhat higher than that of the previous model (Table 5).

Inclusion of higher plants in the photoautotrophic component, as anticipated, increased the total assimilation coefficient of the photoautotrophic component and brought it closer to the human respiratory quotient, so the rate of accumulation of carbon dioxide in the atmosphere decreased to 1 percent of the rate of emission by humans.

In this experiment, before the Chlorella and higher plant components were merged in a single system, each component had been demonstrated capable of supporting the gas exchange of one human. The greenhouse for the plants had a growth area of 15 m^2, and the illuminated surface of the *Chlorella* suspension ranged from 8 to 12 m^2. Illumination levels were comparable. A more important difference between requirements for the plants and algae was that the greenhouse required a total volume of more than 30 m^3, whereas the *Chlorella* reactor occupied a volume almost an order of magnitude smaller. This may be significant when we determine the desirability of including algae in the first space BLSS versions, when all restrictions, including volume, will be stringent.

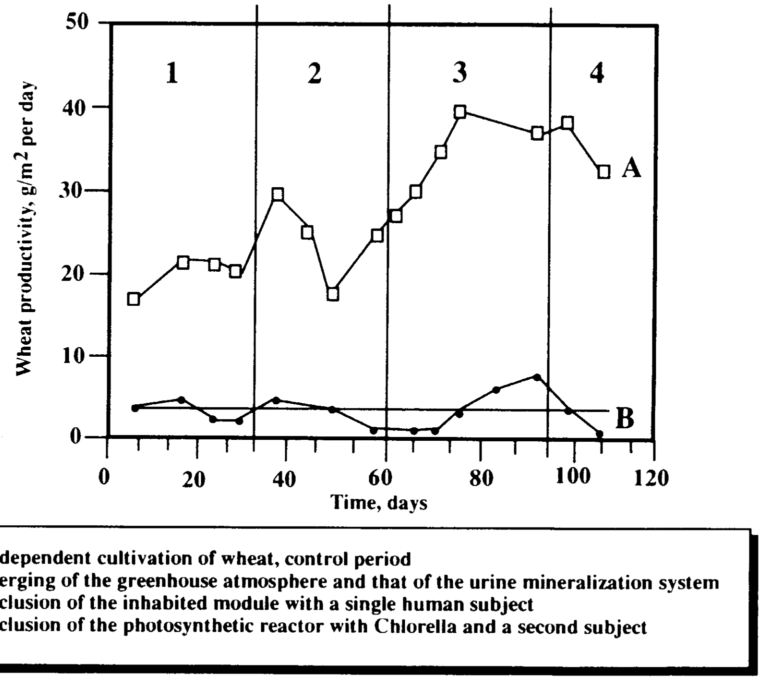


Fig. 16 Dynamics of wheat productivity with respect to total biomass (A) and grain (B) during various stages of BLSS model formation.

Thus, introduction of higher plants into a BLSS based on algae increased the closure of the food and gas exchange cycle. Evidently, further potential for increasing the closure of the system is not very high, since it would require additional production of essential nutrients that represent a comparatively low proportion of the total dietary requirements of humans. At the same time, each additional increase in food production, including animal products, will be obtained at an increasing cost with respect to area, volume, and energy and will require production and processing of an increasingly greater amount of plant biomass and other wastes not utilized in the system. Thus, the degree of closure of the models studied in the U.S.S.R., evidently, is not far short of that which will be attainable and profitable for actual BLSS on spacecraft in the near future.

1. Microflora in Higher Plant Biological Life Support System Models

The inclusion of higher plants in system models led to a qualitative change involving fungi in the composition of microflora in the inhabited module, as has been noted by Tirranen.[55] Before humans were included in the system, fungi in the greenhouse were represented by *Penicillium*. After inclusion of humans, mold spores of the genus *Aspergillus* appeared; by day 10, after closure of the greenhouse, these comprised more than one-half of all fungi. After inclusion of the greenhouse in the "man-algae-micro-organisms" system and by the end of the experiment with the unified system, the *Aspergillus* genus comprised 70–90 percent of the fungi. The major areas where these fungi multiplied were the stalks and ears of wheat. Fungi of the root area of the wheat plants consisted exclusively of members of the genus *Aspergillus*, which were not identified in the atmosphere of the inhabited area.

The predominant bacterial flora of the nutrient solution for the most important plant, wheat, were members of the genus *Pseudomonas*. After inclusion of humans in the system, these were joined by *Ps. Fluorescens*, *Ps. ureae*, and *Ps. aeruglinosa*.[66]

The dynamics of the total level of bacteria in the nutrient solution clearly were a function of the composition of the system model at various stages of the experiment (Fig. 17). After a prolonged period of stability, with a rather low level of bacterial flora during the period of autonomous plant growth, the introduction of a new component into the system (mineralization components, humans, and *Chlorella*) brought a sharp increase in bacteria, followed by a decrease until the next disturbance. Thus, throughout the almost 100-day period of microbiological monitoring, the bacterial flora of the nutrient medium reacted to disturbances as a single microbiocenosis and clearly displayed the capacity for self-regulation of bacterial level.

C. Status of Humans

In all BLSS model experiments the health status of the human subjects was studied not only to ensure their safety during the experiments but also as the major composite indicator for evaluating the appropriateness of the system's environment. A number of studies were directed at identifying possible physiological reactions of human subjects to anticipated abnormalities of the environment (increases in the level

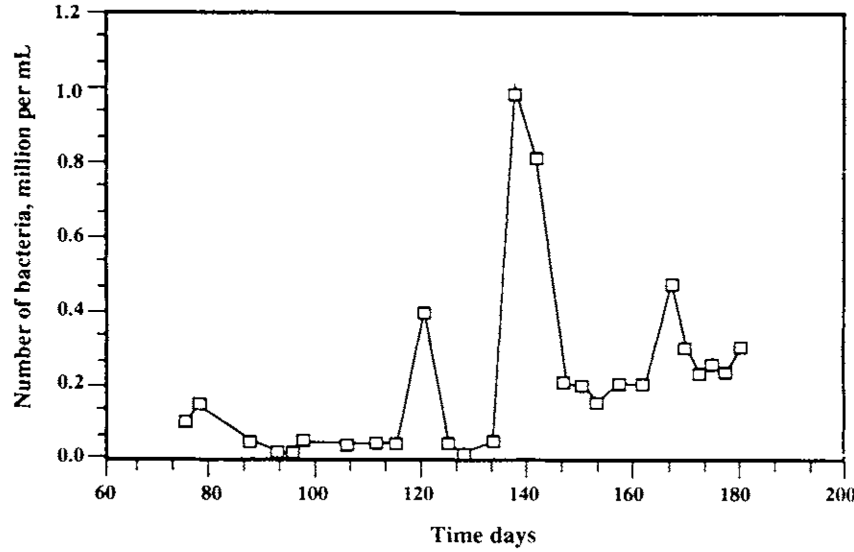


Fig. 17 Dynamics of bacteria content in the nutrient solution of wheat during BLSS model formation.

of carbon dioxide and carbon monoxide) or to unexpected properties of the environment that could affect the immune response. These data on human physiological status have independent significance as important indicators for evaluating the quality of the environment.

Here, we cite data in summary form from all experiments with BLSS models conducted in the Institute of Biomedical Problems.

A common phenomenon in all experiments was an increase in the level of carboxyhemoglobin in the blood of subjects, starting 4–5 days after the experiments began. In an experiment where the level of carbon monoxide in the air was increased during certain periods (reaching 30 mg/m^3), the level of carboxyhemoglobin increased from 5.5 percent during baseline to 14.5 percent on day 5 of the experiment. The quantity of hemoglobin did not show any systematic change and fluctuated throughout the experiments within 3–5 percent of the mean, although the number of erythrocytes sometimes increased toward the end of an experiment. The increase in carboxyhemoglobin was associated with a decrease in the level of the enzyme catalase in erythrocytes starting during the first few days of the experiment. By days 15 through 20 in one experiment, the catalase level had decreased by 30–50 percent of the mean baseline value. The number of erythrocytes by the end of this experiment had increased by 20–25 percent baseline, which can be understood as a compensatory reaction to a partial blockade of the respiratory function of hemoglobin by carbon monoxide.

The only change noted in the examined morphological parameters of peripheral blood was an increase in the number of eosinophils, which, in some cases, reached a level 3–5 times that of the baseline. Both depression of catalase activity of erythrocytes and marked eosinophilia suggest the presence of carbon monoxide intoxication induced by increased levels of carboxyhemoglobin in blood. However, the complete absence of any complaints, not to mention any objective symptoms associated with such intoxication, is difficult to explain. One of the possible explanations for this lack of symptoms of carbon monoxide intoxication may be associated with the gradual increase in levels of carbon monoxide in the atmosphere of the system throughout the first 2 days and the possible triggering of adaptive and/or compensatory processes.

Returning to the eosinophilia, we must also consider another interpretation, this one associated with a possible allergenic effect of the environment. Given the close association of humans and the biological components of the system, exacerbated by the limited area and common atmosphere for all components, one could reasonably expect allergenic or immunogenic phenomena. This aspect of human participation in a BLSS has not been studied. For this reason, in our experiments, under the supervision of I.V. Konstantinova and V.M. Shilov, we studied the status of natural, cellular, and humoral immunity in humans, including active and passive mechanisms. The study of the phagocyte activity of neutrophils, bactericidal activity of blood, and lysozyme activity of saliva in the subjects demonstrated that their participation in these biological systems was not accompanied by any shifts in natural immune status.

Reactivity of lymphoid cells (PHA-blast transformation of lymphocytes) was evaluated on the basis of rate of inclusion of labeled uridine in ribonucleic acid (RNA) synthesis. Here, the results were ambiguous: While, in some cases, there was a significant decrease in lymphocyte reactivity toward the end of the experiments, in other cases, the immune response of lymphoid tissue was unaltered. It is possible that individual differences in the immune systems of the subjects during the experiments were manifested here.

Close contact between the humans and the biological components of the systems and their concomitant microflora, volatile compounds in the atmosphere, and plant pollen naturally raise the possibility of allergenic effects of the environment. We have previously encountered marked food aller-

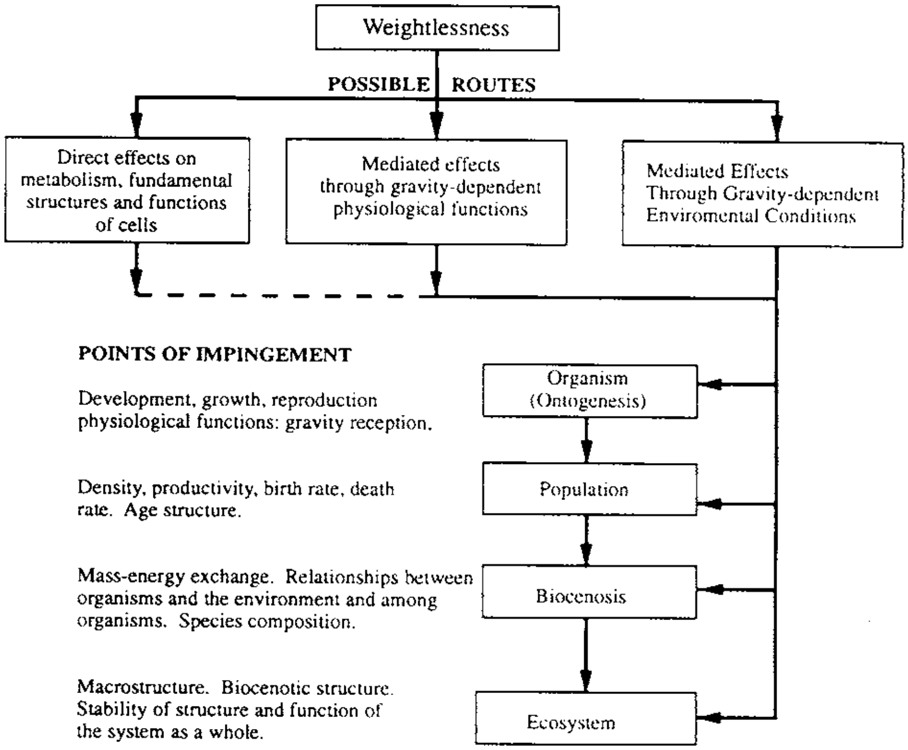


Fig. 18 Possible routes of the effects of weightlessness on living systems and points of impingement at various hierarchical biological levels.

gies after dietary intake of 50–150 grams of *Chlorella* biomass.[67] A similar result was also noted by American authors; however, this was during the period before the technology for cultivating algae was fully developed and still involved long periods of biomass accumulation in experiments. This allowed autolysis to occur, so the composition of the final product used as food was not controlled. In our experiments, *Chlorella* biomass (50 grams of dry weight) was included in the diet immediately after it was obtained from the photosynthetic reactors. The biomass then underwent thermal processing (30 min of boiling), which eliminated confounding factors to permit study of the issue of allergenic properties of *Chlorella* biomass, particularly its proteins, and the protein of concomitant bacteria. This could have been one explanation for the aforementioned eosinophilia. For this reason, under the direction of I.V. Konstantinova, we studied the allergic sensitivities of subjects to possible natural allergens in the systems. We performed allergy tests to bacterial allergens and a water extract from *Chlorella* homogenate but failed to detect sensitivities of the subjects to these allergens.

On the whole, the status of the subjects remained satisfactory throughout the course of the experiments. Toward the end of the period, a slight asthenization (debility) was noted; this could be attributed to the low motor activity and restricted living space, although a set of physical exercises had supported energy expenditure to match the calories in the diet.

Thus, the results of the study of health status of humans, including immunological status, failed to reveal anything not characteristic of healthy individuals in natural environments. The most important composite indicator of the adequacy of the human living environment failed to reveal any sign that the BLSS models studied were unwholesome. In the future, this conclusion will be most important for evaluating experimental models of the BLSS in which the human environment is formed through the activity of only one plant species ("human-algae-micro-organisms") or a small number of higher plants with concomitant microflora.

V. Weightlessness as a Condition of Biological Life Support System Implementation

When working on the problems of the human BLSS, we must assume that for a long time to come (although not forever) weightlessness will be an obligatory condition of space flight. For this reason, all aspects of this issue must be considered from the point of view of the possibility of functioning in microgravity.

Modern gravitational biology, which focuses on the study of the individual organism and its subordinate levels (cellular and subcellular), cannot answer the questions of whether ecological systems can exist in weightlessness, since the decisive factors are the levels above that of the organism—population, biocenosis, and ecosystem. This inspired us to reconsider, if only theoretically, the whole issue of the biological or other significance of weightlessness and possible points of impingement on various hierarchical levels of living systems.

At this stage, it was important to acknowledge that the concept of the biological significance of weightlessness is, in principle, ambiguous. The effects of weightlessness at various levels of biological organization, from the single organism to the ecosystem, may be realized through different routes and different mechanisms. The ideas generated by this analysis are schematically presented in Fig. 18.

The first route—the direct effects of weightlessness on components of biological processes of metabolism, development, growth, and reproduction—has not been persuasively demonstrated. The conclusion that there are no specific effects of weightlessness on these fundamental life processes is being increasingly substantiated. It has been argued that there does not even exist a theoretical rationale for such effects,[68] and we fully concur with this.

The second route is not direct but mediated through changes in the conditions under which the gravity-dependent functions of the organism are realized. Here, we are referring particularly to gravity reception and the associated reactions of circulation, antigravity, and motor functions and associated processes of fluid-electrolyte metabolism. The major relevant data here were obtained from research on long-term human space flights. This research has revealed not only the effects of weightlessness but also its mechanisms realized through gravity-dependent physiological functions.

The third route for the effects of weightlessness is also indirect. Effects are mediated through change in gravity-dependent factors of the environment; that is, through ecological factors. Here, we refer to the gravity-dependent stratigraphic distribution of gases, liquids, and solids, which determines the position of the organism within the medium it inhabits, its motor behavior, the distribution of trophic resources in the environment, and the processes of mass transfer. The absence of sedimentation and thermal convection take on significance here. This route becomes important at the level in which organisms exist in dense populations in the presence of intrapopulation gradients of environment and food resources and competition for these resources. In considerably larger ecosystems, this route becomes absolutely inevitable, since the initial conditions for the appearance and evolution of life on Earth were the gravitationally organized macrostructure of the biosphere and strict limitations on the main living environments—the atmosphere, hydrosphere, and upper layers of the Earth.

The schema in Fig.18 facilitates discussion of another aspect of the possible effects of weightlessness, the issue of the substrate itself, and the points at which it impinges on living systems at various hierarchical levels. Each of these levels is associated with inherent criteria of status. Each level transforms significant changes occurring in the lower levels into its own criteria of status, providing information about this level with its points of impingement and the mechanisms through which the effects of weightlessness are realized.

As is well known, life on Earth is discrete and quantum in nature; and its elementary units, its "quanta," are individual organisms, each with its own sublevels and subsystems, the numbers of which depend on the complexity of structure. The individual organism is also the direct recipient and detector of the effects of any external factors. This is the first and lowest hierarchical level of life and includes all stages of ontogenesis of the individual, from fertilization of the ovum to the adult organism containing the seeds of the next generation. All this composes the ontogenetic level, inexactly referred to as the "organismic"—the first level at which weightlessness impinges on living systems. Points of impingement of weightlessness can, in theory, include all the defining characteristics of life usually cited in definitions: food consumption and metabolism, growth, development, and reproduction. These are characteristic of any organism at any stage of evolutionary development. The ultimate, ecologically significant result of changes occurring at this level may be alterations (more likely decreases) in the viability of the individual, in individual life span, and in reproductive capacity.

However, individuals can only exist in isolation under artificial conditions. In nature, they do not simply exist but coexist with others like them in populations, biocenoses, etc. It follows that the effects of weightlessness at the ontogenetic level can lead to changes at other, higher hierarchical levels. However, this can also fail to occur, since changes at the level of the individual may be balanced through genetic, morphogenetic, and physiological regulation or through the mechanisms of population, interpopulation, and biocenotic regulation that protect every ecosystem.

At the population level, the effects of weightlessness are manifest in the major criteria of population status (density, productivity, age structure, birth rate, and death rate), which reflect not only the current status of the population but also its future prospects.

At the level of biocenoses and ecosystems, the potential effects of weightlessness are still more numerous and heterogeneous and their manifestations are more complex and difficult to predict, since, at these levels, there are complex interactions among many populations. Furthermore, the living environments, which themselves may be altered by weightlessness, typically include all forms of matter—solid, liquid, and gas. Criteria of system status at these levels become more and more general and ultimately amount to preservation or disruption of the stability of the structure and functioning of the ecosystem as a whole.

Thus, the superorganismic levels of living systems not only are subject to the effects of weightlessness but also can serve as tools for evaluating the ecological significance (or lack thereof) of changes occurring at the ontogenetic level. This level is the arena for accumulating adaptive changes and eliminating changes that do not affect the relative viability of individuals in populations and biocenoses.

This discussion has demonstrated the need for a new phase in the development of gravitational biology, in which we focus on the study of living systems at various hierarchical levels of biological organization. In other words, the study of individual changes at the ontogenetic level may be expanded to the study of the long-term fate of these changes in populations, biocenoses, and entire ecosystems.

The major practical conclusion of this analysis of the role of gravity is that the in-flight success of the models of closed ecosystems that have been tested on the ground for space flight cannot be predicted reliably without studying their major performance characteristics in weightlessness. For this reason, we could not content ourselves with a theoretical analysis of the problem but were compelled to move on to its experimental study, despite the drastic increase in the methodological and technical difficulties of conducting such experiments in space.

Even before this, however, we were compelled to confront the possibility of incorrect interpretation of the effects of weightlessness in our study of populations of one-celled algae. In our first experiment with heterotrophic cultures, we found a 50 percent increase in the number of cells in weightlessness compared to control; and, in the second, longer experiment, we found an almost 2-1/2-fold increase compared to control. Similar results were obtained by other authors in the study of the growth of bacteria.[69] Subsequent analyses revealed that, in weightlessness, the algae suspension was distributed along all the internal walls of the rectangular vessel (the "IFS-2" device), whereas, in the ground-based control, it was naturally confined to one wall, the bottom. As a result, the area of air contact in flight was several times greater than in the control. This significantly improved gas exchange conditions for the flight culture and was sufficient to explain the increase in the growth rate of this culture compared to the control (which, therefore, was not an appropriate control).

In subsequent experiments in this series, we used vessels for the ground-control conditions, in which the area of the bottom corresponded to the sum of the interior surfaces of the flight vessels; under these conditions, the rate of growth of the experimental culture did not differ from that of the ground control.[70] In these experiments, the objects of study were *Chlorella* cultures. By the end of the experiment, these cultures contained 10^8–10^9 cells per milliliter; i.e., billions of cells. Actively growing cultures of this size may be considered closed populations.

The population characteristics of the algae studied in flight were unchanged. The number of dead cells and cells with reduced viability remained within normal limits. Ratios among various age groups in the populations also were unchanged. The age structure in all experiments was characteristic of rapidly growing populations, with young individuals dominating. This was typical of the first two to three generations in shorter experiments, and of the fifth generation in the 15-day experiment.[71]

Subsequently, these results were confirmed with actively growing autotrophic cultures of *Chlorella* that served as components of a microecosystem in which the algae supported the gas exchange of the heterotrophic components of the system (fish and micro-organisms) and supported the trophic needs for the organic substance of the concomitant microbiocenoses.[72] Within the ecosystem, the algae also retained their physiological and population characteristics and supported the functioning of the community for the duration of the experiments.

Thus, analysis of the physical (mechanical) conditions of the environment in experiments and introduction of technologically appropriate controls made it possible to establish that the significant acceleration of algae growth in weightlessness found in our initial experiments was not the result of direct effects on mechanisms of growth, development, and reproduction of the cells. Rather, it was mediated by changes in the physical conditions of the environment, which influenced an important ecological factor—conditions of gas exchange between the suspension and the atmosphere. This result demonstrates the potential practical significance of such studies for BLSSs, since the cultivation technologies of various systems may themselves be affected by weightlessness.

The multifaceted role of weightlessness can be observed, also, in studies of the characteristics of embryonal development in quail. In 1979, a joint Soviet-Czechoslovakian experiment was performed involving incubation of quail eggs on biosatellite Cosmos 1129. For technical reasons associated with the biosatellite flight, the period of in-flight incubation was 11-1/2 days, instead of the 18 required for full embryogenesis. The experiment demonstrated that it was possible for an embryo (in some cases, at least) to undergo normal development while exposed to space during the initial critical stages of embryogenesis (which comprise 70 percent of the gestational period). However, the significant number of embryos that failed to develop (35 percent) was striking, as was the high frequency of morphological developmental anomalies, although there were other obvious potential causes [long-term (up to 20 days) storage of the eggs before the beginning of incubation, high temperature (23–28° C) during the last 10 days of storage; and decrease of humidity to 30 percent during the last half of incubation].[73]

A complete incubation cycle of quail eggs occurred on Mir in March 1990 in a Soviet-Czechoslovakian experiment using a second generation incubator manufactured in Czechoslovakia. For the first time, eight normally developed, viable chicks with active motor, vocalization, and appetitive behavior were hatched in weightlessness, a result which definitively supports the conclusion that normal embryogenesis is possible under such conditions.[74] However, even in this experiment, the hatching rate of the chicks was lower than normal, and the number of developmental anomalies in the embryos during various stages was elevated, although (unlike the case in the first experiment) conditions of egg storage before incubation were not adverse and incubation was not interrupted. During flight, there were cases in which the embryo occupied a longitudinal position in the egg and the chick developed in the egg with the head at the narrow end, which prevented them from emerging from the eggs without help. This did not occur in the control condition. Similar anomalies were reported in Ref. 75.

In interpreting the results of experiments on the incubation of eggs in weightlessness, we are evidently dealing with qualitatively different categories of functions. The mechanisms of morphogenetic processes in the course of development of the embryo appear to be rather rigidly determined genetically during all the critical stages and, in themselves, are not affected by weightlessness. This has also been demonstrated with mammals.[76] However, weightlessness may change external conditions for realization of embryogenesis in the egg itself. This seems highly likely when one considers the well-known gravity dependence of the macrostructure of eggs, the components of which (yolk, albumen, air chamber and the embryo itself) normally occupy positions determined by gravity, with an embryo's position fixed with respect to the other components of the egg macrostructure, especially the air chamber. In weightlessness, this internal structure may be retained or disrupted, which may, in turn, disrupt the conditions for embryo metabolism and respiration. In the latter instance, development may halt or be disrupted in some further way, thus becoming an example of the indirect effects of weightlessness.

The first 2–4 days in the lives of the viable chicks hatched in weightlessness revealed a new problem associated with weightlessness, which is important for the practical implementation of a BLSS. During this time, the birds were unable to develop the skills needed for active orientation and maintenance of body position in space. They constantly "floated" within their enclosure, and their chaotic tumbling was exacerbated by increasingly sharp movements of the wings and feet, despite the presence of a guiding air stream intended to propel them toward the grid floor so they could grasp it with their claws. Although they actively pecked food from the cosmonauts' hands, they could not be kept in the vicinity of their feeding dish and it proved impossible to maintain them onboard the station since they could not eat by themselves.

Analyses of videotapes showed that the development of motor skills appropriate to weightlessness was impeded by the innate reflex of pushing off from surfaces, which is natural and expedient for neonates in gravity. It is obvious that this introduces a completely new problem, that of developing appropriate motor behavior in the neonate in an agravitational environment, behavior that is incompatible with instinct. This problem, which can be solved for humans by instruction and training, may become one of the limiting problems for the realization of the BLSS in space and will apply, of course, not only to birds but also to all other free-living organisms.

Further observations were performed on adult birds. In July 1990, three females and one male quail, aged 60–65 days, were delivered to space station Mir. They spent 8 days in flight, including a day of flight in the transport spacecraft. On arrival at Mir, they were placed in the animal enclosure previously used for the chicks, in individual restraining slings that kept them near their feeding dish. Their specially developed feed of a pastelike consistency contained the amount of liquid they needed, so that it was not necessary to develop a special device to supply them with water. Active consumption of food began during the first minutes after the birds were transferred to the chamber from the transport container, which should be of interest to physiologists studying vestibulo-autonomic responses.

Before flight, the birds had been in the stage of active oviparity. During flight, egg laying immediately ceased in all three females. (The last egg was laid by one of the females in the transport spacecraft, and a normal chick hatched from it on the ground.) This was consistent with a morphologically pronounced hypotrophy of the ovaries and oviducts observed immediately postflight. These disorders, noted also in birds of the synchronous control, were attributable to a pattern of nonspecific stress reactions and turned out to be reversible. By days 7 and 8 after landing (and at the same period in the synchronous control), egg laying resumed; and the first eggs laid after flight hatched completely normal, viable offspring. As of this writing, these hatchlings have produced several generations of offspring.

The birds' motor behavior is of some interest. During their time in orbit, one bird was twice freed from the restraining sling and released into the space of the station's work module. The videotape showed that after it had been released from the cosmonaut's hands, it hung motionless for a few seconds but, after the first movement, began to rotate randomly. However, unlike the chicks, the adult bird was soon able to perform short flights until it touched the wall of the module, which it had no way of grasping. On one of these flights, the bird returned to the enclosure and immediately began to peck at its food.

Of course, these observations are not sufficient to assess the potential and actual adaptation of motor behavior to weightlessness in birds. However, there does appears to be a difference, in principle, between the adaptive potential of adult birds and neonates. Adult birds already possess the initial basis for adaptation in the form of established, tested, individually acquired motor skills, although these were developed in a gravitational environment; and, here, we may speak about the adaptation of existing skills to new conditions.

A neonate chick still does not have any individually acquired skills. Thus, it has no initial base that could be adapted, and the innate base (unconditioned reflexes and instincts) is clearly inappropriate to the conditions in which it was born. It is possible that here it would be better not to speak about adaptation but, rather, about a completely new problem: the initial formation of motor skills in an inappropriate environment, from an existing base of clearly unsuitable, unconditioned innate mechanisms. It is clear that this problem is relevant to animals other than birds. One might argue that even human infants will have to confront this problem.

To evaluate the significance of weightlessness for the BLSS over the long term, a general prediction can be derived: As we progress from experimental prototypes and ground-based modeling of closed ecological systems to their practical use in spacecraft, we will increasingly have to consider the effects of weightlessness when selecting biological subjects, develop technologies for cultivating them, and design species and biocenotic structures and food chains for planned ecosystems. It is already quite clear that weightlessness effects will be realized not through primary changes in fundamental vital processes in organisms but through a variety of indirect effects at all levels of biological organization. Such indirect effects ultimately alter the unity of organisms and environment that have developed through evolution, a unity which is an invariant condition for life on Earth in all its manifestations.

All this implies that the problem of the man-rated BLSS cannot be solved merely by balancing the material and energy flows that form the basis of every ecosystem. In studying or designing these flows, we cannot completely abstract them from their carriers—specific organisms with active, individual, and species-specific relationships to the environment, including gravity. These relationships range from spatial orientation in plants to the sensorimotor bases of appetitive, sexual, and other forms of motor behavior in animals at various phylogenetic levels. In microgravity, all this may be disrupted to the extent that it could interfere with the stability of the BLSS as an ecosystem. This situation fully justifies the need for a new, *ecological* phase in the development of traditional gravitational biology, which has accomplished virtually all its original objectives, since it has already provided convincing evidence that fundamental vital processes are independent of gravity. However, it has stopped short of considering the ecological aspects of the individual effects of gravity it has found, including implications for the problem of closed ecological systems. This will require different approaches, subjects, and methods of research.

VI. Mathematical Modeling of Biological Life Support Systems

Before full BLSSs are constructed, mathematical models will be built to explore various aspects of the dynamics of the system and to test the influence of different configurations, the addition of alternative components, and operation during and after various failure modes. Perhaps the most crucial function of the mathematical models at this early stage of development is their ability to formalize and communicate the experimental findings from the disciplines dealing with BLSS components, such as nutrition, crop growth, engineering, and control theory.

These disciplines correspond to the major physical components of the BLSS: the human inhabitants, crops, recycling, and control systems. Each presents its own unique challenges involving modeling and will be examined in turn. These include diet models, crop growth models, engineering models, and models of system dynamics. Finally, we must also ask how these disciplines fit together into the larger picture.

A. Diet Models

Models of human nutrition serve as foundations for the design and analysis of closed life support systems. One of the most sophisticated nutritional modeling studies for closed systems thus far in the United States is NASA's diet design study.[77] This study specified gross diet requirements for protein, lipid, and total energy. In addition, it included essential amino acids, fatty acids, vitamins, and many minerals.

Allowable values for all these substances were set with minima in all cases and with maxima in many cases; for example, total protein and fat-soluble vitamins. These values were matched with a range of foods, including legumes, roots, tubers, seeds, grains, and leafy vegetables. Protein diets comprised both raw and processed foods. The modeling goal, expressed mathematically, was to meet the dietary requirements and minimize total biomass. Wade[77] solved this linear programming problem by applying the simplex method to various food groupings. Various minimized diets were calculated. One diet consisted of spinach, sweet potatoes, rice, sunflower seeds, and wheat sprouts. An important finding of this study was that for any result, given input restrictions on groupings, there were always other diets in which the mix of food had substantially more variety with only slightly more total biomass.

Further efforts along these lines are progressing at Ames Research Center in California.[78] Expert systems can help in coupling potential diets to other requirements for optimizing the design of the entire system. In these studies, the crucial role played by diet models is evident: By specifying the diet, one specifies the crops that are grown and, ultimately, the areas, volumes, and mass flow rates of matter and energy for the particular crops. The design of a diet effects the design of all other parts of a BLSS.

B. Crop Growth Models

Modeling the life cycles of higher plants will be an important part of the closed system design. First of all, crop growth models aid the design of effective crop growth experiments by maximizing the information gained. Since many environmental variables influence crops, such as light quality and quantity, relative humidity, temperature, partial carbon dioxide and partial oxygen pressure, and nutrients, models can reduce the number of experiments required by helping experimenters define the most important questions. For example, Volk and Bugbee[79] found the leaf emergence rate in wheat to be relatively insensitive to cultivar differences and developed a generic response surface to light and temperature; this allows the researcher to focus on other aspects of growth and development during trials of candidate cultivars.

As another example, Bugbee and Salisbury[32] have developed a five-part analysis of crop growth in terms of efficiency in the conversion of photosynthetic photon flux (PPF) into edible biomass. The five steps are 1) conversion of energy to PPF; 2) percentage of absorption of PPF by crops; 3) photosynthetic efficiency (moles of carbon dioxide fixed per mole of PPF absorbed); 4) respiratory carbon use efficiency (losses); 5) harvest index (percentage of edible biomass). Bugbee and Salisbury can evaluate the maximum potentially achievable values and compare these values with their experimental results. This modeling procedure allows them to isolate and set priorities on potential areas for improvement.

A second important function of crop growth models in BLSS design is to provide the input and output flows of matter and energy required for coupling to models of other components of the system, such as waste processors, food processors, and gas exchangers. Carbon dioxide, oxygen, and water flow rates are the major mass flows to be specified by crop growth models. Although there is an extensive literature on crop models for field agriculture (for example, see the work from Groningen, Netherlands), models for crops in closed systems need to be different. For example, closed system models need to be able to evaluate the transpiration rate of water at high carbon dioxide levels, as well as provide rates of oxygen production by the crops. One approach to oxygen production was developed by Volk and Rummel[80] by accounting for oxygen production and consumption associated with the biosynthesis of various tissue components of edible and inedible biomass (protein, carbohydrate, lipid, fiber, and lignin). Volk and Cullingford[81] used this approach in a generic model for the growth of wheat, soybeans, and potatoes and showed the corresponding flows of carbon dioxide and oxygen during the crop life cycle. Because they define explicit material flows, crop models are key components in the design of closed systems.

C. Engineering Models

In the category of engineering models, we consider models of all components except crops and humans. These might be limited to physical and chemical machines and processes; or they might also include biological agents in algal reactors and in waste processing, such as microbial reactors to convert cellulose wastes to usable glucose. Engineering models include all the physical devices to move materials to and from the crops and the humans.

For example, Blackwell and Blackwell[82] have used engineering models to examine the control of the thermal and fluid dynamics for an advanced crop growth research chamber under construction at NASA Ames Research Center. To perform research on crop growth in a closed environment, it is necessary to precisely control variables, such as lighting, temperature, oxygen, carbon dioxide, humidity, atmospheric pressure, and chemistry of the nutrient solution. The component devices for the atmospheric control system include the following devices in a closed loop around the plant growth chamber: heat exchangers, blowers, gas separators and intakes, valves, filters, and sample ports. In addition to the component devices, modeling studies during system development must take into account the measurement instruments and control algorithms that connect the measurements with the actuators of the component devices.

Blackwell and Blackwell[82] and Blackwell[83] describe the application of robust control theory to stabilizing the environment for the advanced crop growth chamber. Formal control procedures will be necessary if the system is to function with little or no human intervention and because special problems arise from the close coupling between the crops and the thermal and fluid parts of the chamber.

D. System Dynamics Models

System dynamics models of BLSSs explore how the entire system—humans, crops, waste processors, and all other components—behaves in time with explicit material cycles. Cycles of materials are crucial to the construction of these models. Note that cycles are neither inherent nor necessary to the nutritional or crop growth models, for these models are parts of the system dynamics models. Engineering models, when coupled with those for crop growth and nutrition, become system dynamics models.

Published studies of system dynamics in BLSSs include Averner,[84] Babcock et al.,[85] and Rummel and Volk.[86] These models consist of storage media for materials linked by processors, which move and transform materials between the storage areas. The Rummel and Volk BLSS model takes advantage of modular construction and has been adopted for further study and development by others at NASA.[87]

The general scheme for the flow of materials in the BLSS model is shown in Fig. 19. The model tracks carbon, hydrogen, oxygen, and nitrogen along pathways of chemical transformation that include 1) biosynthesis of protein, carbohydrate, fat, fiber, and lignin in the edible and inedible parts of plants; 2) food consumption and production of organic solids in human urine, feces, and wash water; and 3) operation of the waste processor. These pathways, as well as others involving water (such as crop transpiration, cooking, and human hygiene), drive mass flows of carbon dioxide, oxygen, water, and nitric acid to and from their individual storage medium or buffer reservoirs.

Experiments with the BLSS model have explored the effects of crop batch size and planting/harvesting schedules; mechanical failures of components, such as the waste processor; biological failures, such as crop disease; and variations in crew size. The model is an essential tool for understanding the behavior of the whole system in response to changes in designs and assumptions about the structure and behavior of the components. One example is shown in Fig. 20.

Figure 20 shows the BLSS model's output for the water in storage during three different possible scenarios for planting and harvesting. All three produce an average of about 800 grams of wheat per person per day (for six persons) and require a 55-day life cycle. One scenario harvests (and plants) a single large crop every 55 days. The other two scenarios have smaller plantings staged at intervals of 11 and 5 days. The oscillations in the water storage in the scenario with the 11-day harvests are about double the size of the oscillations with the 5-day harvests. This is not unexpected, since the growing crop accumulates water (basically in the edible tissues), depleting the water reservoir; and, when the crop is harvested, the inedible plant parts are sent to the waste pro-

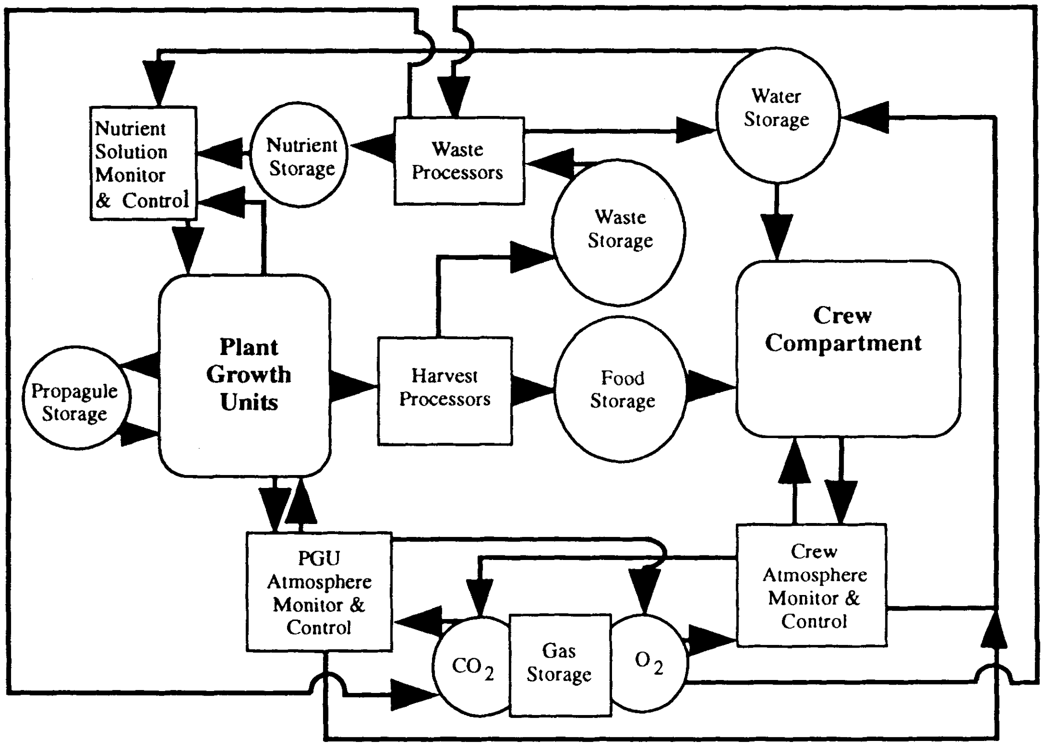


Fig. 19 Schematic of the BLSS model of Rummel and Volk.[86]

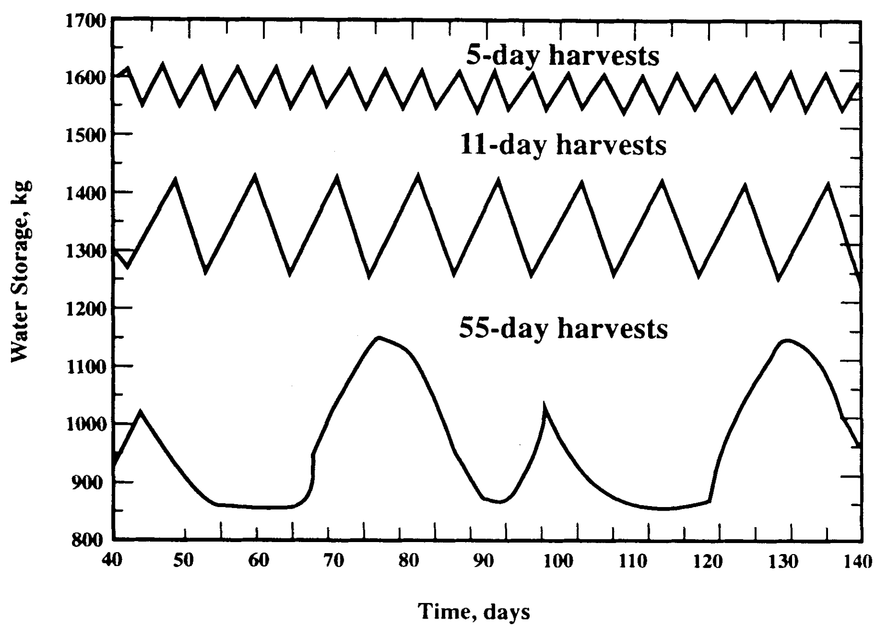


Fig. 20 Output of the BLSS model for water storage as a function of different planting and harvesting schemes. All three cases have the same average daily food production, but harvesting schedule significantly affects the water mass in storage.

cessor, returning the water to storage.

The curve for the 55-day harvest scenario in Fig. 20 illustrates behavior that does not follow from this explanation of how water storage oscillates as a simple function of crop size and planting interval. The naive expectation would be for maximum and minimum water storage every 55 days. Instead, we find that every 55-day cycle has two maxima and two minima and a complicated shape compared to the simple cycles with the 11- or 5-day harvests. Understanding the results of the 55-day harvest requires an examination of all the contributing fluxes to and from water storage. Crop water uptake is governed by a nonlinear crop growth model (a logistic equation with rapid growth early in the life cycle and slower growth later). Water is supplied rapidly from the harvested waste of inedible biomass and more steadily from the stored food. The combination of these processes produces the complicated results shown.

This example is meant to convey a message beyond the mere analysis of water fluxes and water storage dynamics. We expect similar qualitative shifts in the behavior of the system with changes in design parameters in all aspects of a BLSS. Modeling such behavior is essential to the creation of control strategies.[82]

In addition to the system models described above, extensive mathematical modeling of biological systems of particular relevance to the BLSS have been carried out by Yu.M. Svirezhev (Svirezhev and Yelizarov,[88] Svirezhev and Logofet[62]). The subjects covered by Svirezhev include models in biogeocenology and the problem of optimal productivity of populations, "predator-prey" interactions, trophic structures, population age structures, the stability and reliability of biological communities, and artificial closed biological systems.

VII. Conclusion

1) The current state of BLSS development can be attributed mainly to research on models created in the U.S.S.R. in the 1970s and 1980s. One general conclusion about the functioning of such models is that it is possible to attain complete regeneration of the atmosphere and water, 95–99 percent utilization of carbon dioxide, and 10–26 percent regeneration of food. These models have demonstrated that humans can survive in an isolated environment formed by a limited set of plant organisms (including a one-member set—*Chlorella*) and their concomitant microflora. Under these conditions, with the exception of O_2:CO_2 balance, there is no evidence for lack of stationarity of the major functional characteristics of the models that would suggest any maximum duration of their existence. The processes within the system can be regulated through intrinsic regulation mechanisms with minimal control from without. Today, these models have accomplished virtually all of the tasks that were initially set for them. The next generation of BLSS models must differ from the first by virtue of greater closure of the substance cycle through the participation of heterotrophic organisms in transforming unused organic wastes into food biomass, thus returning them to the trophic chains of plants. Full-scale realization of such models will be most effective using all the experience that has been obtained to date within international programs.

2) The development of life support systems for space has also led to a new understanding of the potential relationship between biological and physical-chemical systems. For a long time, such systems were perceived as competitors, but there were no winners in this contest. The physical-chemical directions that previously seemed so promising have not yet led to the creation of even ground-based models that can fully regenerate the atmosphere and water without dead-end processes. However, man-rated models of BLSSs, which perform a greater range of functions, have long been developed and tested.

As a result, the long-standing competition between physical-chemical and biological systems has inevitably been resolved through a natural compromise—acknowledgement of the need to create a life support system with parallel processes utilizing physical-chemical and biological technologies; i.e., the need to create a system that is neither exclusively physical-chemical nor biological. There is still no agreed-upon name for such systems; here, we call them mixed or hybrid.

3) The first official expression of this direction is the international CELSS Program (NASA, U.S.A.), with the goal of a life support system for Space Station and subsequent spacecraft. This program mandated the creation of just such a mixed system. Development of its biological components is currently in the phase of laboratory research.

However, the creation of mixed systems is virtually irrelevant to the main goal—modeling of BLSSs as relatively closed ecological systems—since mixed systems are controlled and monitored by external systems, instead of the mechanisms of internal self-control that are characteristic of biological systems at all hierarchical levels.

4) The first attempts to analyze the ecological consequences of weightlessness showed that they may act as barriers to the realization of the BLSS in general and, in particular, to the interactions among their components that have been postulated without considering the specific organisms involved and their responses to conditions of weightlessness. This pessimistic conclusion with regard to orbital flights is not valid for lunar and planetary bases, where the weightlessness factor does not exist. Under these conditions, altered gravity becomes, for terrestrial life forms, simply a quantitative variant of the normal gravitational environment, to which the life form can be adapted, first physiologically and then, possibly, though evolution. For the future, what is important is that this aspect of gravitational biology not be excluded from consideration in BLSS projects in the relatively near term.

5) The need to design and implement full-scale models of the conditions of human existence in complete isolation from the Earth's environment will lead, ultimately, to recognition that it is necessary to introduce this same "terrestrial environment" into these models. In other words, full-scale modeling of relatively well-developed BLSSs that are functional equivalents of the natural environment of humans are required. The interdisciplinary scale of this task has no analogs in the history of science—it is unprecedented. We have merely touched upon it in this chapter, neglecting problems of engineering and, partially, technology.

6) Today, no one nation possesses sufficient theoretical, scientific, biotechnological, and technical knowledge, not to mention experience with practical modeling of man-rated BLSSs, to reliably design second-generation BLSS models suitable for the manned space missions of the 21st century. It would seem to follow that reliable biomedical support of fu-

ture manned space programs can be most effective if based on the pooling of efforts and expertise acquired during the more than 30 years of work in creating models of biologically appropriate living environments for the extrabiospheric spacecraft of the future.

References

[1]Tsiolkovskiy, K.E. Exploration of outer space with jet rockets. *Collected Works*, vol. 2. Moscow, U.S.S.R. Academy of Sciences, pp. 128–130 (in Russian).

[2]Bowman, N.I. The food and atmosphere control problem in space vessels, Part II, The use of algae for food and atmosphere control. *Journal of the British Interplanetary Society*, 1953, no. 12, pp. 159–167.

[3]Burlew, I.S. *Algal Culture from Laboratory to Pilot Plant*. Washington, D.C., Carnegie Institute, 1953, p. 600.

[4]Myers, J. Basic remarks on the use of plants as biological gas exchangers in a closed system. *Journal of Aviation Medicine*, vol. 25, no. 4, 1954, pp. 407–412.

[5]Sisakyan, N.M.; Gazenko, O.G.; and Genin, A.M. Problems of space biology. In: Sisakyan, N.M., and Yazdovskiy, V.K., Eds. *Problems of Space Biology, Volume 1*, Moscow, U.S.S.R. Academy of Sciences, 1962, pp. 17–26 (in Russian).

[6]Sisakyan, N.M.; Parin, V.V.; Chernigovskiy, V.N.; and Yazdovskiy, V.K. Some problems in space research and exploration. In: Sisakyan, N.M., and Yazdovskiy, V.K., Eds. *Problems of Space Biology, Volume 1*, Moscow, U.S.S.R. Academy of Sciences, 1962, pp. 5–16 (in Russian).

[7]Semenenko, V.Ye.; Vladimirova, M.G.; and Nichiporovich, A.A. Intensification of photosynthetic productivity of a culture of one-celled algae. *Izvestiya AN SSSR, Seriya Biologicheskaya*, 1962, no. 2 (in Russian).

[8]Shepelev, Ye.Ya. The ecological system on space flights. *Aviatsiya i Kosmonavtika*, 1963, no. 1, pp. 20–25 (in Russian).

[9]Shepelev, Ye.Ya. Man-rated life support systems based on biological substance cycles in the cabins of spacecraft. In: Yazdovskiy, V.I., Ed. *Space Biology and Aerospace Medicine*. Moscow, Nauka, 1966, Chapter 14, pp. 330–362 (in Russian).

[10]Gaume, J.G. Plants as a means of balancing a closed ecological system. *Journal of Astronautics*, 1957, no. 4, pp. 72–75.

[11]Gafford, R.D., and Craf, C.E. A photosynthetic gas exchanger capable of providing for respiratory requirements of small animals. SAM 58-124, Randolph AFB, Tex., USAF School of Aviation Medicine, 1959, pp. 58–124.

[12]Myers, J.I. Study of photosynthetic regenerative systems on green algae. SAM 58-117, Randolph AFB, Tex., USAF School of Aviation Medicine Report, 1958, vol. 58, p. 117.

[13]Gazenko, O.G. Space biology. In: *Development of Biology in the U.S.S.R., Soviet Science and Technology after 50 Years, 1917–1967*, Moscow, Nauka, 1967, pp. 613–631 (in Russian).

[14]Bovee, H. H.; Christensen, G. M.; Zommers, I.; and Thompson, J. M. Life support parameters in the space environment. In: *Advances in Astronautical Science (Proceedings), Volume 9*, New York, 1963, pp. 336–344.

[15]Genin, A.M. Some principles underlying the formation of artificial living environments in the cabins of spacecraft. In: Sisakyan, N.M., and Yazdovskiy, V.I., Eds. *Problems of Space Biology, Volume 3*, Moscow, Nauka, 1964, pp. 59–65 (in Russian).

[16]Shepelev, Ye.Ya. Some problems in human ecology under conditions of closed substance cycle systems. In: Sisakyan, N.M., and Yazdovskiy, V.I., Eds. *Problems of Space Biology, Volume 4*, Moscow, Nauka, 1965, pp. 169–179 (in Russian).

[17]Gazenko, O.G., and Shepelev, Ye.Ya. Development of the ideas of K.E. Tsiolkovskiy on a biological method for supporting the habitability of spacecraft. In: *Proceedings of the 6th Lecture Series on Development of the Scientific Legacy of K.E. Tsiolkovskiy*, Moscow, U.S.S.R. Academy of Sciences, 1972, pp. 3–6 (in Russian).

[18]Shepelev, Ye.Ya. Biological life support systems. In: Calvin, M., and Gazenko, O.G., Eds. *Foundations of Space Biology and Medicine*, Washington, D.C., NASA Hq., vol. 3, chapter 10, pp. 274–308.

[19]Gazenko, O.G., and Shepelev, Ye.Ya. Long-term space flights and the human living environment. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1977, no. 1, p. 10 (in Russian).

[20]Gazenko, O.G.; Grigoryev, A.I.; Meleshko, G.I.; and Shepelev, Ye.Ya. Habitability and biological life support systems. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1990, no. 3, pp. 12–17 (in Russian).

[21]Vernadskiy, V.I. *Thoughts of a Naturalist*. Moscow, Nauka, 1977, p. 191 (in Russian).

[22]Telitchenko, M.M. Formation of biologically complete water by hydrobionts. In: *Biological Self-Purification and the Generation of Water Quality*, Moscow, Nauka, 1975, pp. 9–14 (in Russian).

[23]Kholodnyy, N.G. The biological significance of volatile organic substances emitted by plants. In: Kholodnyy, N.G. *Natural and Laboratory Environments*, Moscow, Moscow Society of Natural Scientists, 1949, pp. 156–173 (in Russian).

[24]Petryanov-Sokolov, I.V., and Sutugin, A.G. Aerosols in nature and industry. *Priroda*, 1933, no. 3, pp. 2–11 (in Russian).

[25]Bondaryov, L.G. The role of plants in the migration of mineral substances into the atmosphere. *Priroda*, 1981, no. 3, pp. 86–90 (in Russian).

[26]Bazilevich, N.I.; Rodin, L.Ye.; and Rozov, N.N. How much does the living substance of our planet weigh? *Priroda*, 1971, no. 1, pp. 46–53 (in Russian).

[27]Boychenko, M.M. On the formation of water quality by hydrobionts. *Nauchnyye Doklady Vysshey Shkoly, Biologicheskiye Nauki*, 1975, no. 4, pp. 74–77 (in Russian).

[28]Hoff, J.E.; Howe, J.M.; Mitchell, C.A.; and Carry, A. Nutritional and cultural aspects of plant species selection for

a regenerative life support system. NASA Contractor Report 166324, Moffett Field, CA, NASA Ames Research Center, 1982.

[29]Salisbury, F.B. Bioregenerative farming on the Moon. In: *Proceedings of the 8th International Academy of Astronautics (IAA) Man in Space Symposium*, Tashkent, U.S.S.R., Sept. 29–Oct. 4, 1989.

[30]Ashida, A.; Yoshioka, T.; Tanakura, S.; Takatski M.; Ysa, T.; Koisumi, M.; Oguchi, M.; and Nitta, K. Plant system for a lunar base. In: *Proceedings of the 8th IAA Man in Space Symposium*, Tashkent, U.S.S.R., Sept. 29–Oct. 4, 1989.

[31]Midorikawa, Y.; Fuji, T.; Terai, M.; Omasa, K.; and Nitta, K. A food/nutrient supply plant for lunar base CELSS. Paper presented at the 40th Congress of the International Astronautical Federation (IAF), Madrid, 1989.

[32]Bugbee, B., and Salisbury, F.B. Current and potential productivity of wheat for a controlled environment life support system. *Advances in Space Research*, vol. 9, no. 8, 1989, pp. 5–15.

[33]Lisovskiy, G.M., Ed. *A Closed Man-Higher Plants System. A 4-Month Experiment.* Novosibirsk, 1978, p. 138 (in Russian).

[34]Ivanova, I.Ye.; Derendyayeva, T.A.; Alekhina, T.P.; and Shaydorov, Yu.I. The higher plant component in man-rated biological life support systems. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1990, no. 4, pp. 40–43 (in Russian).

[35]Shepelev, Ye.Ya; Shaydorov, Yu.I.; and Popov, V.V. Reprocessing of plant wastes on a solid substrate for a man-rated biological life support system. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1983, no. 6, pp. 71–74 (in Russian).

[36]Yazdovskiy, V.I., and Ratner, G.S. Heterotrophic organisms—one of the sources for human nutrition on long-term space flights. In: Chernigovskiy, V.N., Ed. *Work Performance, Issues of Habitability and Biotechnology. Problems of Space Biology, Volume 7*, Moscow, Nauka, pp. 382–388 (in Russian).

[37]Antsyshkina, L.M.; Kirilenko, N.S.; Mamontov, V.Ya.; Melnikov, G.B.; and Ryabov, F.P. Experience maintaining fish in airtight aquaria with and without *Chlorella*. In: Sisakyan, N.M., and Yazdovskiy, V.I., Eds. *Problems of Space Biology, Volume 4*, Moscow, Nauka, 1965, pp. 646–654 (in Russian).

[38]Mironova, N.B. Comparative evaluation of the growth of Tilapia (*Tilapia massambica*, Peters) fed on *Chlorella* and other food. In: Chernigovskiy, V.N., Ed. *Work Performance, Issues of Habitability and Biotechnology. Problems of Space Biology, Volume 7*, Moscow, Nauka, 1967, pp. 505–512 (in Russian).

[39]Burenkov, M.SA., and Agre, A.L. Preliminary evaluation of the potential for using land molluscs as components of closed ecological systems. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1975, no. 4, pp. 90–91 (in Russian).

[40]Meleshko, G.I.; Shepelev, Ye.Ya.; Guryeva, T.S.; Bodya, K.; and Sabo, V. Embryonal development of birds in weightlessness. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1991, no. 1, pp. 37–39 (in Russian).

[41]Takahashi, Y. Water oxidation waste management systems for a CELSS—the state of the art. *Biological Science in Space*, vol. 3., no. 1, 1989, pp. 45–54.

[42]Golubeva, Ye.G., and Yerofeyeva, T.V. Dynamics of growth of house fly larvae on wastes of a biological life support system. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1982, no. 6, pp. 74–76 (in Russian).

[43]Andre, M., and MacElroy, R.D. Plants and man in space. A new field in plant physiology. *Physiologist*, vol. 33, no. 1, (Suppl.), 1990, pp. S100–S101.

[44]MacElroy, R.D., and Smernoff, D.T., Eds. Controlled ecological life support systems. *Advances in Space Research*, vol. 7, no. 4, 1987, pp. 1–153.

[45]MacElroy, R.D.; Tibitts, T.W.; Thompson, B.G.; and Volk, T., Eds. Natural and artificial ecosystems. *Advances in Space Research*, vol. 9, no. 8, 1989, pp. 1–202.

[46]Dean, R.B.; Golub, M.A.; and Wydevan,T., Eds. Waste management in space. *Waste Management and Research*, vol. 9, no. 5, 1991, pp. 323–490 (whole issue).

[47]Takahashi, Y.; Wydevan, T.; and Koo, C. Subcritical and supercritical wet oxidation of CELSS model wastes. *Advances in Space Research*, vol. 9, no. 8, 1989, pp. 99–110.

[48]Wydevan, T.; Tremor, J.; Koo, C.; and Jacquez, R. Sources and processing of CELSS waste. *Advances in Space Research*, vol. 9, no. 8, 1989. pp. 85–97.

[49]Gitelzon, J.I.; Kovrov, B.G.; Lisovskiy, G.N.; Okladnikov, Yu.N.; Rerberg, M.S.; Sidko, F.Ya.; and Terskov, I.A. *Man-rated Experimental Ecological Systems. Problems of Space Biology, Volume 28*, Moscow, Nauka, 1975 (in Russian).

[50]Meleshko, G.I., and Shepelev, Ye.Ya. Biological life support systems. In: Gazenko, O.G., Ed. *Handbook of Physiology*, Moscow, Nauka, 1987, pp. 30–36 (in Russian).

[51]Meleshko, G.I., and Shepelev, Ye.Ya. Biological life support systems. In: *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, vol. 22, no. 6, 1988, pp. 30–36 (in Russian).

[52]Sinyak, Yu.Ye. Water supply. In: Gazenko, O.G., Ed. *Handbook of Physiology*, Moscow, Nauka, 1987, pp. 340 (in Russian).

[53]Anisimov, B.V. Hygienic significance of ionization of the cabin atmosphere on manned spacecraft. In: Nefyodov, Y.G., Ed. *Sanitary, Hygienic, and Physiological Aspects of Inhabited Spacecraft. Problems of Space Biology,Volume 42*, Moscow, Nauka, 1980, pp. 68–79 (in Russian).

[54]Kondratyeva, Ye.M. Study of the group composition of concomitant microflora during long-term cultivation of *Chlorella* in a closed system. In: Gazenko, O.G., Ed. *Urgent Problems in Space Biology and Medicine*, Moscow, Institute of Biomedical Problems, 1975, pp. 112–113 (in Russian).

[55]Tirranen, L.S.; Gitelzon, J.I.; and Rerberg, M.S. Formation of the microflora component of higher plants in a man-rated closed ecological system. In: *Proceedings of 5th Con-*

gress of the All-Union Microbiological Association, Yerevan, 1975, p. 85 (in Russian).

[56]Yunusova, L.S.; Kondratyeva, Ye.M.; and Drova, N.A. Formation of a microbial cenosis of the photoautotrophic component in a man-rated biological life support system. In: *Micro-organisms in Artificial Ecosystems*, Novosibirsk, Nauka, 1985, pp. 143–146 (in Russian).

[57]Gitelzon, J.I.; Manudovskiy, N.S.; Pankova, I.M.; Posadskaya, M.N.; Somova, L.A.; and Tirranen, L.S. *Microbiological Problems of Closed Ecological Systems*, Novosibirsk, Nauka, 1981, p. 197 (in Russian).

[58]Zaloguyev, S.N.; Viktorov, A.N.; and Startseva, N.D. Sanitary-microbiological and epidemiological aspects of habitability. In: Nefyodov, Y.G., Ed. *Sanitary, Hygienic, and Physiological Aspects of Inhabited Spacecraft, Problems of Space Biology, Volume 42*, Moscow, Nauka, 1980, pp. 80–140 (in Russian).

[59]Drugova, N.A.; Chernova, L.S.; and Mashinskiy, A.L. Formation of a microbial cenosis of wheat plants under conditions of spacecraft habitability. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1989, no. 5, pp. 39–43 (in Russian).

[60]Viktorov, A.N., and Novikova, N.D. Characteristics of the formation of microflora on structural materials used in inhabited pressurized closed environments. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1985, no. 2, pp. 66–69 (in Russian).

[61]Kholodnyy, N.G. What's new in the aeroponic nutrition of plants. *Priroda*, 1951, no. 2 (in Russian).

[62]Svirezhev, Yu.M., and Logofet, D.O. *The Stability of Biological Communities*, Moscow, Nauka, 1978, p. 352 (in Russian).

[63]Shepelev, Ye.Ya., and Meleshko, G.I. Analysis of certain mechanisms underlying the stability of biological life support systems using the example of a culture of one-celled algae. In: *Proceedings of the 8th Lecture Series Dedicated to Developing the Scientific Legacy and Ideas of K.E. Tsiolkovskiy*, Kaluga, Sept. 14–17, 1973, Moscow, U.S.S.R. Academy of Sciences, 1974, pp. 76–84 (in Russian).

[64]Cook, J. Ecology of space flight. In: Odum, E.P., Ed. *Fundamentals of Ecology*, Philadelphia, W.B. Saunders, 1959, Chapter 20.

[65]Guryeva, T.S. Study of the potential for using leaf and stem mass of higher plants to obtain food products in a man-rated life support system. Thesis abstract, Moscow, Institute of Biomedical Problems, 1982, p. 37 (in Russian).

[66]Yunusova, L.S.; Kondratyeva, Ye.M.; and Drugova, N.A. Study of the microflora of the autotrophic component in a man-rated biological life support system. In: *Proceedings of the 11th All-Union Working Meeting on the Substance Cycle in Closed Systems Based on Vital Activity of Lower Organisms*, Kiev, Naukova Dumka, 1983, pp. 173–185 (in Russian).

[67]Kondratyev, Yu.I.; Bychkov, B.P.; Ushakov, A.S.; and Shepelev, Ye.Ya. The use of the biomass of one-celled algae to feed humans. In: Chernigovskiy, V.N., Ed. *Work Performance, Issues of Habitability and Biotechnology. Problems of Space Biology, Volume 7*, Moscow, Nauka, pp. 363–370 (in Russian).

[68]Parfenov, G.P. *Weightlessness and Elementary Biological Processes. Problems of Space Biology. Volume 57*, Moscow, Nauka, p. 272 (in Russian).

[69]Kordyum, G.P.; Polivoda, L.V.; and Mashinskiy, A.L. The effect of space flight conditions on micro-organisms. In: Dubinin, N.P., Ed. *Gravity and the Organism. Problems of Space Biology, Volume 33*, Moscow, Nauka, 1976, pp. 238–260 (in Russian).

[70]Meleshko, G.I.; Shepelev, Ye.Ya.; Kordyum, V.A.; Shetlik, I.; and Doukha, I. Weightlessness and its effect on micro-organisms and plants. One-celled algae. In: Gazenko, O.G., Ed. *Results of Medical Research Performed on the Salyut-6–Soyuz Orbital Scientific Research Complex*. Moscow, Nauka, 1986, pp. 369–380 (in Russian).

[71]Sychev, V.N.; Levinskikh, M.A.; and Livanskaya, O.G. Study of the growth and development of *Chlorella* exposed to space on Cosmos-1887. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1989, no. 5, pp. 35–39 (in Russian).

[72]Levinskikh, M.A., and Sychev, V.N. Growth and development of one-celled algae in space flight as part of an "algobacterial cenosis-fish" system. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1989, no. 5, pp. 32–35 (in Russian).

[73]Shepelev, Ye.Ya.; Bodya, K.; Mishchenko, V.F.; Fofanov, V.I.; Deshevaya, O.A.; Belak, M.; Sidorenko, L.A.; Peter, V.; et al. Outcome of an experiment on the incubation of quail eggs in weightlessness. In: *Abstracts of Papers Presented at the 11th Meeting of the Working Group on Space Biology and Medicine, Intercosmos*, Bucharest, 1982, pp. 121–122 (in Russian).

[74]Meleshko, G.I.; Shepelev, Ye.Ya.; Guryeva, T.S.; Bodya, K.; and Sabo, V. Embryonal development of birds in weightlessness. *Kosmicheskaya Biologiya i Aviakosmicheskaya Meditsina*, 1991, no. 1, pp. 37–39 (in Russian).

[75]Kokorin, I.I.; Pigareva, M.D.; Palmbakh, L.R.; Afanasyev, G.D.; and Mashinskiy, A.L. Embryonal development of quail in weightlessness. In: Dybinin, N.I., Ed. *Biological Research on Salyut Space Stations*, Moscow, Nauka, 1984, pp. 139–144 (in Russian).

[76]Serova, L.V.; Denisova, L.A.; Lavrova, Ye.A.; Makeyeva, V.F.; Natochin, Yu.V.; Pustynnikova, A.M.; and Shakhmatova, Ye.I. Parameters of reproductive functions of animals. Characteristics of embryos and placentae. In: Serova, L.V., Ed. *Ontogenesis of Mammals in Weightlessness*, Moscow, Nauka, 1988, pp. 72–79 (in Russian).

[77]Wade, R.C. *Nutritional Models for a Controlled Ecological Life Support System (CELSS): Linear Mathematical Modeling*. NASA CR 4229, Washington, D.C., NASA Hq., 1989.

[78]NASA. A diet expert subsystem program for the controlled ecological life support system. Contract NAS2-12991, Moffett Field, Calif., NASA Ames Research Center, 1990.

[79]Volk, T., and Bugbee, B. Effects of light and tempera-

ture on leaf emergence rate in wheat and barley crop. *Crop Science*, vol. 31, no. 5, 1991, pp. 1218–1224.

[80]Volk, T., and Rummel, J. D. Mass balances for a biological life support system simulation model. In: MacElroy, R.D., and Smernoff, D.T., Eds. *Controlled ecological life support systems,* NASA Conference Publication 2480, Moffett Field, Calif., NASA Ames Research Center, 1987, pp. 139–146.

[81]Volk, T., and Cullingford, H. Crop growth and associated life support for a lunar farm. In: Mendell, W., Ed. *Lunar Bases and Space Activities of the 21st Century*, Houston, Lunar and Planetary Institute, 1991.

[82]Blackwell, A. L., and Blackwell, C.C. A modeling system for control of the thermal and fluid dynamics of NASA CELSS Crop Growth Research Chamber. Paper presented at the 19th Intersociety Conference on Environmental Systems, San Diego, Calif., July 24–26, Society of Automotive Engineers (SAE) paper 89-1570, 1989.

[83]Blackwell, A. L. A perspective on CELSS control issues. In: MacElroy, R.D., Ed. *Controlled Ecological Life Support Systems: CELSS '89 Workshop*, NASA TM 102277, Moffett Field, Calif., NASA Ames Research Center, 1990, pp. 327–353.

[84]Averner, M. M. An approach to the mathematical modeling of a controlled ecological life support system. NASA-CR-166331, Moffett Field, Calif., NASA Ames Research Center, 1981.

[85]Babcock, P.S.; Auslander, D.M.; and Spear, R.C. Dynamic considerations of control of closed life support systems. *Advances in Space Research*, vol. 4, no. 12, pp. 263–270, 1984.

[86]Rummel, J. D., and Volk, T. A modular BLSS simulation model. In: MacElroy, R.D., and Smernoff, D.T., Eds. *Controlled Ecological Life Support System,* NASA Conference Publication 2480, Moffett Field, Calif., NASA Ames Res arch Center, pp. 56–66, 987.

[87]Cullingford, H. S. Development of the CELSS Emulator at NASA JSC, Controlled Ecological Life Support Systems. In: MacElroy, R.D., Ed. *Controlled Ecological Life Support Systems: CELSS '89 Workshop*, NASA TM 102277, Moffett Field, Calif., NASA Ames Research Center, pp. 319–325, 1990.

[88]Svirezhev, Yu.M., and Yelizarov, Ye.Y. *Mathematical Modeling of Biological Systems. Problems of Space Biology, Volume 20*, Moscow, Nauka, 1972 (in Russian).

[89]Gitelzon, I.I.; Terskov, I.A.; Kovrov, B.G.; Sidko, F.J.; Lisovskiy, G.M.; Okladnikov, Yu.N.; Belyanin, V.N.; Trubachov, I.N.; and Rerberg, M.S. Life support system with autonomous control employing plant photosynthesis. *Acta Astronautica,* 1976, vol. 3, no. 9–10, pp. 633–650.

[90]Gitelzon, I. I.; Terskov, I. A.; Kovrov, B. G.; Lisovskiy, G. M.; Sidko, F. J.; Okladnikov, Yu. N.; Trubachov, I. N.; Pankova, I. M.; Gribovskaya, I. V.; Denisov, G. V.; and Shilenko, M. P. Closed ecosystem as the means for outer space exploration by men. Preprint IAF-81-164, 1981, pp. 1–5.

[91]Lisovskiy, G.M.; Terskov, I.A.; Gitelzon, I.I.; Sidko, F.J.; Kovrov, B.G.; Shilenko, M.P.; Polonskiy, V.I.; and Ushakova, S.A. Experimental estimation of functional abilities of higher plants as medium regenerators in life-support systems. Preprint IAF-81-169, XXIIth IAF Congress, Rome, 1981, pp. 1–4.